Department of Biotechnology and Chemical Technology

Material and energy balance of solid recovered fuel production

Muhammad Nasrullah

Aalto University

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Abstract

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Abstract

The quality of solid recovered fuel (SRF) holds the key to its market demand and utilization for power production. However, the lack of consistency in the quality and availability of SRF may limit its applications in power producing industries. In the SRF production, proper sorting of input waste's components into the relevant output streams is a decisive factor in defining the quality and yield of the SRF.

The objective of this research work was to establish the material and energy balance of SRF production based on an in-depth analysis and detailed evaluation of physical and chemical characteristics of the input and output streams and waste components produced in industrial-scale SRF production. The SRF was produced from three different types of waste materials: commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and municipal solid waste (MSW).

In the case of SRF produced from MSW, higher yields of material were recovered in the form of SRF as compared with that recovered from C&IW and C&DW. Of the MSW input to the process, 72 wt. % was recovered as SRF, equivalent to 86 % energy recovery. In the case of SRF produced from C&IW, a higher mass fraction of the input chlorine (Cl), lead (Pb) and mercury (Hg) was found in the SRF as compared with the SRFs produced from C&DW and MSW, namely 60 %, 58 % and 45 %, respectively. The SRF produced from C&DW was found to contain the lowest mass fraction of the input chlorine, lead and mercury in comparison with the SRFs produced from C&IW and MSW, namely 34%, 8% and 30%, respectively. In each case of the SRF production, a higher mass fraction of the input cadmium (Cd) was found in the SRF than in the other output streams. Among the waste components, rubber, plastic (hard) and textile (synthetic type) were identified as the potential sources of polluting elements and potentially toxic elements (PTEs). In C&IW, C&DW and MSW, rubber was measured to contain 8.0 wt. %, 7.6 wt. % and 8.0 wt. % of chlorine, respectively. In C&DW, plastic (hard) and textile (especially synthetic type) were measured to contain 7.0 wt. % and 3.8 wt. % of chlorine respectively.

The results of this thesis can be used by the SRF manufacturers and users in order to enhance and implement their understandings about the quality and yield of SRF and the research institutes/organisations to make use of the generated data, in waste management and waste-to-energy related modelling and decision making tools.

Keywords Solid recovered fuel, material and energy balance, polluting and potentially toxic elements

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''In the name of ALLAH, most Gracious, most Compassionate''.
''All the praises be to ALLAH, the Lord of the worlds''.

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I hope this thesis provides a step forward in the knowledge and science concerning solid recovered fuel, specifically about the material and energy balance of solid recovered fuel production. The thesis mainly consists of experimental work based measurements, analysis and interpretation of results regarding the in-depth physical and chemical characterisation of input and output streams and waste components produced in commercial scale solid recovered fuel production.

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Muhammad Nasrullah
Espoo, November 2015

List of Abbreviations and Symbols

a.r.	As-received basis of material
C&DW	Construction and demolition waste
CEN	European Committee for Standardization
CHP	Combined heat and power
CHNSO	Carbon, Hydrogen, Nitrogen, Sulphur, Oxygen
C&IW	Commercial and industrial waste
D_{95}	Top nominal size
d.	Dry basis o material
GCV	Gross calorific value
HHW	Household waste
ICP-MS	Inductively coupled plasma mass spectrometry
ICP-OES	Inductively coupled plasma optical emission spectrometry
MBT	Mechanical biological treatment
MFA	Material flow analysis
MSW	Municipal solid waste
MT	Mechanical treatment
NCV	Net calorific value
NIR	Near-infrared
PTEs	Potentially toxic elements
PVC	Polyvinyl chloride
RDF	Refuse derived fuel
SRF	Solid recovered fuel
wt. %	Weight %

List of Publications

The thesis is based on the compilation of the following publications which are referred to by the corresponding numbers:

I. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste, *Waste Management*, volume 34, Issue 8, August 2014, Pages 1398 – 1407.

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III. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., Mass, energy and material balances of SRF production process. Part 2: SRF produced from construction and demolition waste, *Waste Management*, volume 34, Issue 11, November 2014, Pages 2163 – 2170.

IV. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Koskinen, J., Elemental balance of SRF production process: Solid recovered fuel produced from construction and demolition waste. *Fuel,* volume 159, Issue 1, November 2015 Pages 280 – 288.

V. Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., Mass, energy and material balances of SRF production process. Part 3: SRF produced from municipal solid waste, *Waste Management & Research*, volume 33, Issue 2, February 2015, Pages 146 – 156.

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Author's Contribution

I. The author planned and designed the experimental work along with co-authors, conducted the experimental work, analysed the results and wrote the paper.

II. The author was involved in planning the experimental work with co-authors. The author analysed the results, performed the calculations of data generated from the experimental work's measurements and wrote the paper.

III. The author carried out and planned the experimental work, analysed the results obtained from the experimental campaign, performed the calculations and wrote the paper.

IV. The author planned the experimental work along with the co-author, performed the analysis and calculations of the results obtained from the experimental work and wrote the paper.

V. The author conducted the experimental work as designed and planned, analysed the results of the experiments, performed the calculations and wrote the paper.

VI. The author planned the experimental work along with the co-authors, analysed the results, performed the calculations of the experimental data and wrote the paper.

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1. Introduction

1.1 Background

The field of 'waste' is of great importance all around the world. Even in the developed countries, the waste sector is somewhat of a grey area. The amount of waste is increasing dramatically around the globe due to rapid urbanization, population growth and changes in lifestyle. The global generation of municipal solid waste (MSW) is likely to reach 2.2 billion tonnes per year by 2025 (World Bank, 2012). This brings more pressure, responsibility as well as opportunities for the waste management sector.

Proper waste management is vital, not only to deal with the issues related to the environmental and health impact on our society, but also in ensuring resource efficiency and sustainable economic growth. A sustainable modern integrated waste management system should include effective waste prevention, effective source separation practices, and all the possible recycling activities without entailing excessive resource consumption, efficient biological treatments of organic fractions and energy recovery from materials that cannot be efficiently recycled (Brunner and Rechberger, 2014; Bosmans et al., 2013; Arena and Gregorio, 2014). In the EU, waste prevention and management legislation is summarized in a five-step Waste Hierarchy (European Commission, 2008). In this hierarchy, waste prevention is the best option, followed by reuse, recycling and recovery, with disposal such as landfill as the last option. It is recognized that in a fully sustainable waste management system no single process is suitable for all waste streams (McDougall et al., 2001; Brunner, 2010; Ionescu et al., 2013; Santibañez-Aguilar et al., 2013; Menikpura et al., 2013). The EU Waste Framework Directive also notes that, if supported by life cycle thinking, options lower down the hierarchy may be adopted in some circumstances, if they provide a better environmental solution in terms of waste management (European Commission, 2008).

Globally, solid waste disposal is responsible for about 3 - 4% of anthropogenic greenhouse gas (GHG) emissions (IPCC, 2006). In the EU-27, the waste management sector was responsible for 3% of the total GHG emissions generated in 2011 and solid waste disposal accounted for 74% of all the waste management greenhouse gas (GHG). In Finland, in 2011, waste management had a 3% equivalent share of total GHG emissions, and the share of waste disposal from waste management GHG emissions was 84% (United Nations, 2013; Eurostat, 2013). Methane is the most significant GHG emission source from

waste landfills. According to the Finnish government decree (EU regulations) on landfills (Eurostat, 2013), waste containing over 10% biodegradable materials measured by the total organic carbon or ignition loss is banned from landfill; this is due to come into force on 1 January, 2016.

The EU-25 annually generated 241 million tonnes of MSW (Eurostat, 2009), roughly half (49%) of which is landfilled (Kloek and Jordan, 2005) and 17% is incinerated. According to the EU, the diversion of municipal solid waste (MSW) from landfilling to composting, recycling and energy recovery could mean a reduction from 40 to over 100Mt CO_2 equivalents per year; and for the EU-15, this corresponded to 29% of the total GHG reduction target under the Kyoto protocol (European Parliament, 2006; Commission of the European Communities, 2005). Theoretically, with an average electric efficiency of 25% (Gohlke and Martin, 2007) and having a lower heating value of 11 MJ/kg (IPCC Bureau, 2006; U.S. Department of Energy, 2007), 184 TWh of electricity could be generated through MSW combustion, which corresponds to 5.7% of the total electricity generation in the EU-25 (Eurostat, 2009). In comparison, the US generates 250 Mt of MSW annually, of which landfilling accounts for 54% and incineration 13% (United States Environmental Protection Agency, 2008).

High efficiency power generation from waste through gasification or combustion effectively requires knowledge of the physical and chemical properties of the waste (as fuel). In Europe, energy recovery from waste has been adopted as one of the sustainable waste management options to reduce the amount of non-hazardous waste for landfilling. The recovery of energy from MSW is essential in order to achieve the goals set for waste utilization. Direct waste incineration has several issues, for example it requires the construction of dedicated incineration plants, besides having direct environmental impacts and poor public acceptance. This effectively demands the production of solid recovered fuels (SRFs). The use of solid recovered fuel (SRF) and its development has become an interesting option as a suitable alternative for fossil fuels in already existing power production plants. Significant work has been allocated to downstream system research, i.e. thermal treatment; however, comparatively, much less research effort has been put into the fuel preparation stage, and scientific publications on the subject are very few.

The emphasis of this research work is on the comprehensive study of SRF production, based on an in-depth evaluation and detailed characterisation of the input and output streams of material produced in commercial-scale SRF production. The SRF production process is thoroughly examined, and each fuel preparation stage is closely studied. The quality of SRF is comprehensively analysed and presented in terms of the mass, energy, material and elemental balances of SRF production. The SRF studied was produced on industrial scale from three different types of waste material by mechanical treatment (MT).

In this research work, three different types of waste material were used for the production of SRF separately. These waste materials were collected from the metropolitan area of Helsinki region in Finland. The Helsinki region includes four cities; Helsinki, Vantaa, Espoo and Kauniainen with population of

about 1.1 million. These types of waste material colleted and used to produse SRF are;

- Commercial and industrial waste (C&IW): It is solid waste generated by the commercial and industrial sector (shopping centres, offices, warehouses, logistics, manufacturing organizations and retail outlets, etc.) and institutions (educational institutions, medical centres' offices
- and government offices, etc.). It mainly contains paper & cardboards, plastic, textile, wood, rubber, metal and inert (stones and glass).
- Construction and demolition waste (C&DW): It is solid waste generated or produced during the destruction/demolition of buildings. The major components of C&DW were building material (stone, rock, concrete, and sand), wood, metal and plastic. In Finland, C&DW contains more combustibles (especially wood) as compared with C&DW in central Europe.
- Municipal solid waste (MSW): the stream of MSW used here was energy waste collected from households. This energy waste (fraction) was not subject to recycling but to energy recovery. The energy waste (fraction) was source-separated at the household level and contained more than 75 wt. % of energy-related waste components, for example, paper & cardboard, plastics, textile, wood, rubber and foam material and a small wt. % of non-energy waste related components such as inert material (metals, glass, stones) and food waste due to some false sorting.

The detailed physical and chemical characterisations of C&IW, C&DW and MSW are described in Chapters 3, 4 and 5 respectively.

1.2 Solid Recovered Fuel (SRF)

Solid recovered fuel (SRF) is prepared from non-hazardous waste to be utilized for energy recovery in incineration/co-incineration plants and meeting the classification and specifications requirements laid down in CEN standards (EN 15359). Here 'prepared' means processed, homogenized and upgraded to a quality that can be traded amongst producers and users. In the mentioned context here incineration mainly involves combustion and gasification processes.

SRF is becoming a significant contributor to the agenda of international resource and energy efficiency (Velis et al., 2013). SRFs are seen as important contributors to a sustainable EU waste management and contribute to the security of energy supply for the EU, representing a significant potential storable source of indigenous energy (Lund, 2007; Caspary et al., 2007). In Europe, the SRF trade is a reality (Velis and Copper, 2013) and is becoming a major route for energy from waste throughout Europe (Velis et al., 2011). China and Korea are fast-developing economies that are considering widespread use of SRF in co-combustion (Carone, 2008; Choi et al., 2012; Lorber and. Ragoßnig, 2012). One of the major advantages of SRF is that it possesses the biogenic content of

the initial waste stream, which is carbon dioxide (CO_2) neutral and is an alternative energy source that can partly replace the fossil fuels in heat and power producing industries.

In Europe, SRF is produced from different types of waste streams, for example household waste (HHW), commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and from some selected streams of waste material (Velis et al., 2013; Rada and Ragazzi, 2014; Lorber and Ragoßnig 2012). In Europe, SRF is produced in mechanical treatment (MT) or mechanical biological treatment (MBT) plants (Ragazzi and Rada, 2012; Velis et al., 2011; Ionescu et al., 2013; Rada and Ragazzi, 2014). In MT plants, various unit operations/sorting techniques are applied (for example, shredding, screening, magnetic and eddy current separation, pneumatic separation, optical sorting and near-infrared (NIR) sorting) to sort input waste material into various output streams to produce SRF.

SRF is used as fuel/co-fuel in cement kilns, lime kilns, coal-fired power plants, industrial boilers and gasification and combustion based combined heat and power (CHP) plants for the production of energy (power and heat), which reduces the amount of waste going to landfill and replaces fossil fuels to a significant extent. In Europe, the largest CHP and power plant capacities for SRF utilization are currently in Germany, Finland and Sweden (EN15443). The estimated possible use of SRF in the long run (EU-27, 2020) in cement kilns, coal-fired power plants and CHP plants is 24-43 million tonnes/year (ERFO).

In the last years, the term used for the fuel generated from MSW has undergone some changes. In the technical literature, the most common name used to be refuse-derived fuel (RDF), before the more recently adopted term, solid recovered fuel (SRF). These changes are driven by new regulation and accompanying standards. By the early 1990s, an initial disaster cycle for RDFs was effectively closed and the term ended up denoting a low-quality fuel or absence of quality checks (Velis and Copper, 2013). Due to the high concentrations of chlorine and heavy metals, RDFs could not create enough market demand (Rotter et al., 2004). The challenges around RDF at that time were not significantly different to those of today (Velis and Copper, 2013). SRF is clearly distinguished from RDF. The major difference is that SRF is manufactured in compliance with CEN standards (EN15359), whereas RDF is not. The principle for distinguishing SRF from RDF is shown in Figure 1.

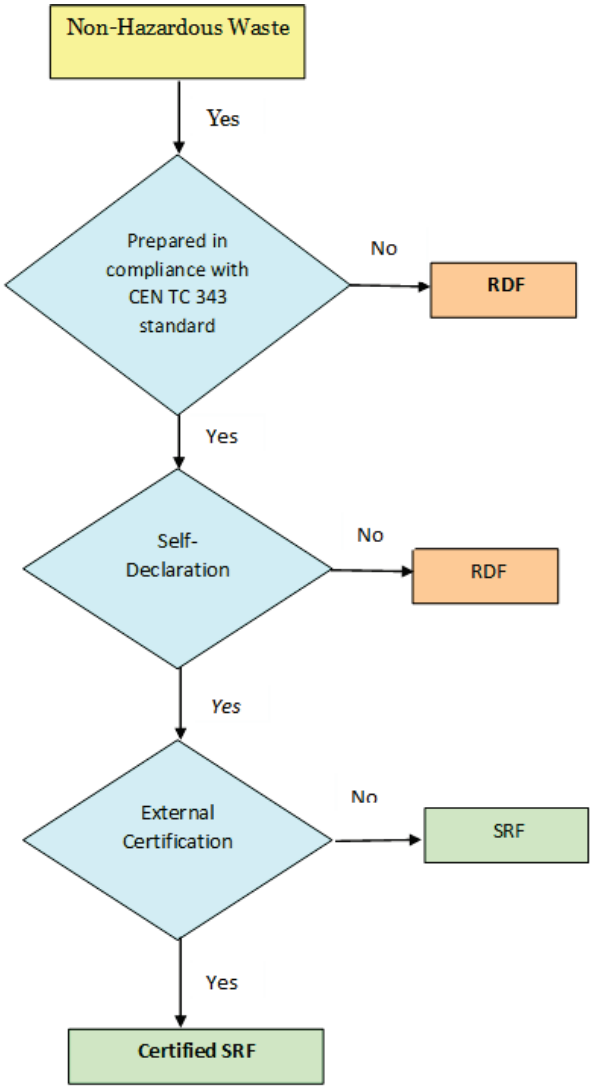


Figure 1: Principle for distinguishing SRF from refuse-derived fuel (ERFO)

1.3 Classification of SRF

The classification system for SRF (EN 15359) is based on three important fuel properties: an economic parameter (net calorific value), a technical parameter (chlorine content) and an environmental parameter (mercury content). The classification system for SRF is given in Table 1.

The fuel properties are:

- Mean value for net calorific value (NCV; as-received basis)
- Mean value for chlorine content (dry basis)
- Median and 80th percentile values for mercury content (as-received basis)

Table 1: Classification systems for solid recovered fuel (EN 15359)

Classification property	Statistical measure	Unit	Classes				
			1	2	3	4	5
Net calorific value (NCV)	Mean	(MJ/kg)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	Mean	% (d)	≤ 0.2	≤ 0.6	≤ 1.0	≤ 1.5	≤ 3
Mercury (Hg)	Median	mg/MJ (ar)	≤ 0.02	≤ 0.03	≤ 0.08	≤ 0.15	≤ 0.50
	80th percentile	mg/MJ (ar)	≤ 0.04	≤ 0.06	≤ 0.16	≤ 0.30	≤ 1.00

Only those fuels that are derived from non-hazardous waste and meet the CEN standards for SRF can be classified as SRFs. However, the classification of SRFs may not be sufficient for the user. The user has to have a further detailed description of the fuel based on general/specific requirements. Relevant fuel properties can be further specified between the user and producer of SRF. Some critical fuel properties need to be specified, whereas others can be described voluntarily or upon user request (EN 15359).

1.4 Quality of SRF

The quality of SRF is key for its future market demand and utilization as a mainstream fuel, especially in power-producing industries. The quality of SRF is often defined in terms of homogeneity (composition), energy efficiency (heating value) and environmental and technical parameters (concentration of a certain element, especially chlorine and heavy metals). Quality assurance for SRF implies that the heating value and concentration of chlorine (Cl) and mercury (Hg) are as per the CEN standards for SRF (EN 15359) and moreover, the concentration of heavy metals is to be kept as low as possible. For SRF to be accepted as a replacement for conventional fuels (fossil fuels), especially in the power generation industry, it is of utmost importance to achieve good quality in terms of homogeneity, energy efficiency and environmental and technical parameters. An overview of the validation programme regarding technical specifications (TSs) to guarantee the quality of SRF and examination of the implementation of quality management of the whole SRF production process is presented in “Quality management organization, validation of standards, developments and inquiries for solid recovered fuels” (Gawlika et al., 2007).

In Europe, SRF is produced from various types of non-hazardous waste material such as commercial and industrial waste (C&IW), construction and demolition waste (C&D waste) and household waste (HHW) and sewage sludge and some other selected streams of waste material. In an MT or MBT SRF production plant, based on the unit operations/sorting techniques, the input waste stream is divided/classified into various output streams such as

fine fraction, ferrous metal, non-ferrous metal, heavy fraction, reject material and SRF as process product.

The mass flow of the input waste stream components (paper & cardboard, plastic, textile, wood, rubber etc.) in the relevant output streams of SRF production plays a decisive role in defining the quality of SRF. In an SRF production plant, there is a strong connection between the proper sorting of input waste stream components into the relevant output streams and the quality and yield of SRF. The sorting of the input waste stream components into the output streams is significantly affected by the properties of the components (i.e. in terms of moisture content, particle size distribution and particle shape of the components) (Nasrullah et al., 2014a; Nasrullah et al., 2015b). In SRF production, unit operations/sorting techniques and their arrangements (in terms of plant flow sheet/configuration) have a significant impact on the quality of SRF. In MT/MBT SRF production plants, the functionality in terms of capacity and the performance of air classifier and near-infrared (NIR) sorting units play a vital role in the proper sorting of the combustible/non-combustible components of the input waste stream into SRF and other than SRF streams (i.e. reject material and heavy fraction).

A low confidence level in the quality, limits the applications of SRF as a mainstream fuel. An in-depth knowledge of the physical and chemical characteristics of the waste components and, input and importantly, the output streams of SRF production is essential for the understanding of SRF quality. Here, in this context, the physical characteristics include composition, appearance (in terms of particle size, shape and colour of components), weight/density and moisture content, and the chemical characteristics include heating value and elemental (i.e. halogen, heavy metals and trace elements) composition. The physical and chemical characteristics of the output streams of SRF production are directly related to the type and mass fraction of the input waste stream's components into the output streams. Understanding of the materials flow (i.e. components of input waste) through SRF production facilities can be very useful for SRF manufacturers in order to optimize plant configurations (i.e. flow sheet/arrangements of unit operations) to produce SRF with specific and predictable quality and yield.

There are a number of research studies (Dunnu et al., 2010a; Dunnu et al., 2010b; Montané et al., 2013; Rada and Andreottola, 2012; Kemppainen et al., 2014; Arena and Gregorio, 2014a) which present quality-related data on SRF in terms of its physical and chemical properties. In contrast, there are hardly any published studies available that evaluate and examine in detail the physical and chemical properties of the input and output streams of SRF production. Publications analysing the detailed characterization of the input and output streams produced in the commercial-scale SRF production process in terms of their physical and chemical characteristics are hard to find. There is limited published research (Velis et al., 2011; Velis et al., 2013; Rotter et al., 2004) dealing with certain aspects of the said issue for SRF/RDF.

1.4 Objective of the work

The objective of this research work was to establish the material and energy balance of solid recovered fuel (SRF) production based on an in-depth and detailed analysis and evaluation of the physical and chemical characteristics of waste components and the input and output streams produced in industrial-scale SRF production. Based on the material and energy balance, the mass flow of waste components (paper & cardboard, plastics, wood, textile, rubber), energy content and more importantly polluting and potentially toxic elements (PTEs) from input waste stream into the output streams of SRF production were determined. The polluting and potentially toxic elements included: chlorine (Cl), lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg). The SRF studied was produced from commercial and industrial waste (C&IW), construction and demolition waste (C&DW) and municipal solid waste (MSW) through mechanical treatment (MT) on full industrial scale. In this research work, the central issues addressed regarding the production of SRF were:

1. The link between SRF quality and the mass flow and share of waste components from the input waste stream into the output streams.
2. The effect of process parameters (i.e. characteristics of input waste feedstock and performance of unit operations used in the process) on the sorting/distribution of waste components into the relevant output streams.
3. The effect of the type of input waste stream on the quality of SRF.

1.5 Thesis organization

This thesis consists of a summary part, and six appended peer-reviewed journal publications, Paper I - VI. The summary of the thesis is discussed in the first six chapters.

Chapter 1 consists of the introduction and relevant background of the subject and the objective of the work. In Chapter 2, the methodology employed to conduct this research work and the experimental set-up is explained and presented. The standard methods of sampling and analysis are described in detail. Chapter 3 summarises the results of mass, energy, material and elemental balances of SRF production from commercial and industrial waste (C&IW). Chapter 4 presents the main results regarding mass, energy, material and elemental balances of SRF production from construction and demolition waste (C&DW). Chapter 5 presents the results of mass, energy, material and elemental balances of SRF production from municipal solid waste (MSW). In Chapter 6, the major results of the work related with material and energy balances, identification of waste components containing polluting and potentially toxic elements (PTEs) and the energy consumed to produce SRF and power available from produced SRF are compared and discussed and the relevant areas of future research are identified. Finally, based on the major findings and results of this research work, conclusions are drawn.

2. Methodology

2.1 Experimental set-up

The research work was based on three industrial-scale experimental campaigns in which solid recovered fuel (SRF) was produced from three different types of waste material through mechanical treatment (MT). The three types of waste material used to produce SRF were:

- Commercial and industrial waste (C&IW)
- Construction and demolition waste (C&DW)
- Municipal solid waste (MSW): Energy waste collected from household

The quantity of C&IW, C&DW and MSW used to produce SRF separately, was 79 tonnes, 74 tonnes and 30 tonnes, respectively. Waste materials were collected from the metropolitan area of the Helsinki region and transported to an MT-based waste sorting plant to produce SRF. Waste collection points were well separated throughout this region. Waste material was collected by trucks/lorries from their respective collection locations.

2.2 Process description

Waste material is treated in the MT-based waste sorting plant to produce SRF. Unit operations/sorting techniques used in the MT plant were: primary shredding, screening (jigging and drum screens), magnetic and eddy current separation, air classification, near-infrared (NIR) sorting units and secondary shredding, as shown in simplified flow diagram Figure 3. Sorting processes (i.e. unit operations) are designed for material sorting based on material properties, e.g. particle size (screening), density/weight (air classification), magnetic properties (magnetic separation) and infrared (IR) spectra (NIR sorting). Mechanical processing of input waste material concentrates suitable waste components into a prepared suitable combustible fraction stream of SRF, and separates out recyclables (metals) and polluting/contaminated and non-combustible waste components into separate small streams. The function of each unit operation/sorting technique used in the MT plant to produce SRF is explained below.

2.2.1 Primary shredding

In primary shredding, the particle size of input waste stream components is reduced to a smaller size (i.e. up to a nominal top size of D_{95} 150 mm). In addition, primary shredding is useful in homogenizing, dealing with large and hard components and opening the closed plastic bags of the input waste stream.

2.2.2 Screening

Screening is the subsequent unit operation used after primary shredding. In screening, jigging and drum screens are used. Waste components having a particle size of D_{95} <15 mm are screened out as fine fraction and components with a large particle size (>300 mm) are separated to be sent back to primary shredding. Waste components having a particle size of between D_{95} 15 mm and 300 mm are treated in further unit operations.

2.2.3 Magnetic and eddy current separation

Components of ferrous and non-ferrous metals are separated out in magnetic and eddy current separators, respectively. Several magnetic and eddy current separating units are used at various locations in the process to recover the maximum amount of metals from the input waste stream for recycling.

2.2.4 Air classification

Light density/weight components (such as paper and cardboard, plastics, textile, foam and wood etc.) are separated in a wind shifter/air classifier and put into the SRF stream. In the wind shifter, air flows in the cross-direction of the falling material and separates lightweight components from heavy and medium-weight components.

2.2.5 Near-infrared (NIR) sorting

Near-infrared (NIR) sensor sorting is based on the near-infrared/specific spectral properties of the components of the waste material. In the NIR sensor, signals are transferred by advanced software to the air nozzles at the end of the conveyor belt and combustible particles are shot over the separating wall into the SRF stream. In the process, the near-infrared (NIR) sensor was set for positive sorting and recognized suitable/combustible components (e.g. paper & cardboard, wood, non-PVC plastics, textile etc.) to put into the SRF stream. Unsuitable/ non-combustible waste components (PVC plastic and other highly chlorinated/contaminated components and inert material) ended up in the reject material stream. The NIR-based sorting technique and principle are explained in detail (Reich, 2005). An automated sorting unit based on NIR technology is shown in Figure 2.

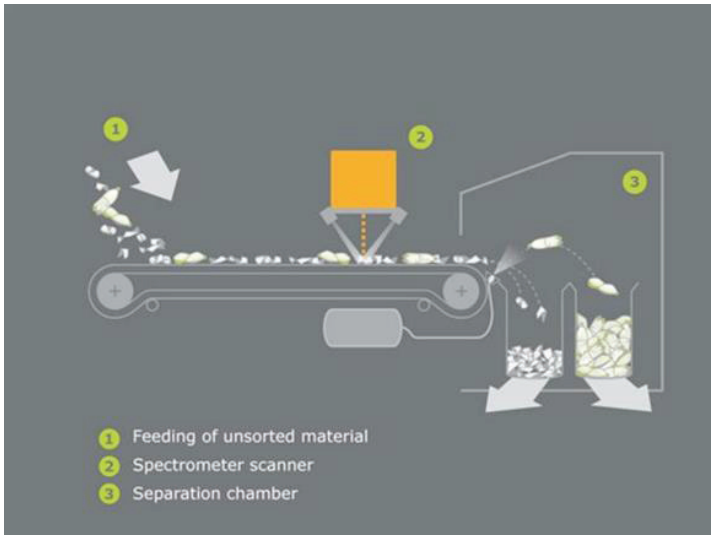


Figure 2: Automated sorting unit based on NIR technology (TITECH/TOMRA)

2.2.6 Secondary shredding

Secondary shredding is the final unit operation in the MT plant in which the particle size of the SRF stream is reduced to < 80 mm. After secondary shredding, SRF is ready to be delivered to customers either as loose material or baled and wrapped.

2.3 Process streams

Based on the unit operations/sorting techniques used in the MT waste sorting plant, the input waste stream was further divided/classified into the various output streams of material, as shown in Figure 3. The input waste streams were C&IW, C&DW and MSW for the three different experimental campaigns. The output streams were:

- Solid recovered fuel (SRF)
- Fine fraction
- Heavy fraction
- Reject material
- Ferrous metal
- Non-ferrous metal

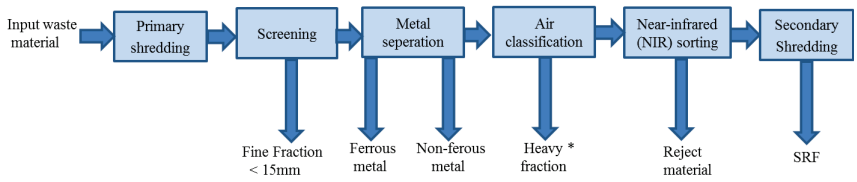


Figure 3: Simplified mechanical treatment process to produce SRF [Paper I]

* In air classification, lightweight components were separated and put in the SRF stream, whereas heavy weight/density components (stones/rock or metallic pieces etc.) were left out as heavy fraction.

2.3.1 Use of the output streams

SRF is a process product and utilized as fuel/co-fuel for energy production in combined heat and power (CHP) gasification and combustion plants; metals (ferrous/non-ferrous) are recycled and streams of reject material, fine fraction and heavy fraction (based on their composition) are utilized partly for energy recovery, environmental construction (landfill construction) and disposal in landfill.

2.4 Sampling methodology

All the process streams (input and output) were sampled from the SRF production plant and further treated for their preparation for laboratory analysis according to CEN standard methods for SRF as mentioned below;

- EN 15442, Solid recovered fuels – methods for sampling.
- EN 15443, Solid recovered fuels – methods for the preparation of the laboratory sample.

2.4.1 Sampling of process streams from SRF production plant

The representativeness of samples of the input and output streams taken from the SRF production plant was ensured by following the CEN standard methods for SRF: EN 15442 Solid recovered fuels – methods for sampling. The methods applied for the sampling of input and output streams from the SRF production plant were:

- Sampling from a static lot
- Manual sampling from a static conveyor belt
- Manual sampling from a drop flow

The sampling method used was based on the operating conditions and practical situation of the SRF production plant and process streams. As per EN

15442, the sampling increment size of process streams was based on their respective top nominal size (D_{95}) and bulk densities, and 24 increments of each stream (except ferrous metal, non-ferrous metal and heavy fraction) were collected. Streams of ferrous metal, non-ferrous metal and heavy fraction were comparatively (i.e. as compared with other streams) homogeneous in their composition, and therefore, it was not necessary to take more than 4 increments for each of these streams. The top nominal size (D_{95}, mm) and sampling quantities of the input and output streams from the SRF production plant are given in Table 2.

Table 2. Sampling quantities of process streams taken from the SRF production plant [Paper I]

Process stream	Top nominal size D_{95} (mm)	Increment size [b] (kg)	Combined sample [c] (kg)
Input waste stream[a]	150	20	480
SRF	75	2.5	60
Reject (D_{95} 85mm)[d]	85	5.0	120
Reject (D_{95} 120mm)[d]	120	10	240
Fine fraction	10	1.0	24
Heavy fraction	150	20	80
Ferrous metal	150	20	80
Non-ferrous metal	150	20	80

[a] Input waste stream represents C&IW, C&DW and MSW used separately in three experimental campaigns. Samples were taken after primary shredding.
[b] Increment size is the portion of material extracted in a single sampling operation.
[c] Combined sample is the sum of 24 increments for the input waste stream, SRF, reject streams and fine fraction, and the sum of four increments for heavy fraction, ferrous metal and non-ferrous metal.
[d] There were two streams of reject material, separated based on their particle size distribution, i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm).

The sampling increments of respective streams were combined together to make combined samples of each stream. The top nominal (D_{95}) sizes of process streams were provided by the plant authorities.

2.4.2 Sample preparation of stream's samples for laboratory analysis

The objective was to reduce the original size (mass) of the process stream's combined samples (see Table 2) to a laboratory test sample size (mass) without changing the original composition of the samples. In order to maintain the representativeness of the original samples, the sample preparation for laboratory analysis was performed according to EN 15443: Solid recovered fuels –

methods for the preparation of the laboratory sample. The sample preparation of stream's samples for laboratory analysis was performed in two stages:

- Sample preparation outside the laboratory
- Sample preparation in the laboratory

As per EN 15443, two methods were applied at each stage of sample preparation:

- Particle size reduction
- Sample division (mass reduction)

Sample preparation outside the laboratory:
The particle size reduction of stream samples was done by using a shredder and sieves of various mesh sizes. The top nominal size (D_{95}) of each stream (except metals) was reduced to 30 mm. The fine fraction was not further shredded as it already had a D_{95} of 10 mm. The sample size (mass) at each step after particle size reduction was reduced by the manual increment division method (EN 15442). The metals in each stream were not included in the sample preparation. After sample preparation outside the laboratory, the prepared samples of the input waste stream, SRF, reject (D_{95} 85 mm), reject (D_{95} 120 mm), fine fraction and heavy fraction streams were reduced to 15 kg and that of the fine fraction (D_{95} 10 mm) to 5 kg and sent to the laboratory for further sample preparation and final analysis.

Sample preparation in the laboratory:
In the laboratory, the set-up of apparatus/equipment used for further sample preparation of the stream samples was a cutting mill, crushing mill, grinding mill and riffle divider. This apparatus/equipment was applied in series to reduce the top nominal size (D_{95}) and mass size of samples at each stage of sample preparation. The top nominal size of samples was further reduced by the cutting, crushing and grinding mills from 30 mm to 20 mm, 10 mm and 0.5 mm respectively. The riffle divider was used to reduce the sample size (i.e. sample mass) at every stage after particle size reduction. Through this procedure, the top nominal size (D_{95}) was reduced to 0.5 mm and the mass size to 0.5–5 g of samples of each stream as the final laboratory test analysis sample. The procedure of sample preparation for laboratory analysis of process streams in the laboratory is illustrated in Figure 4. Both reject streams, i.e. reject (D_{95} 85 mm) and reject (D_{95} 120 mm), were combined together into one sample stream as reject material for final laboratory analysis.

Details of the process description, sampling of process streams from the SRF production plant and sample preparation for laboratory analysis are given in the appended Paper I.

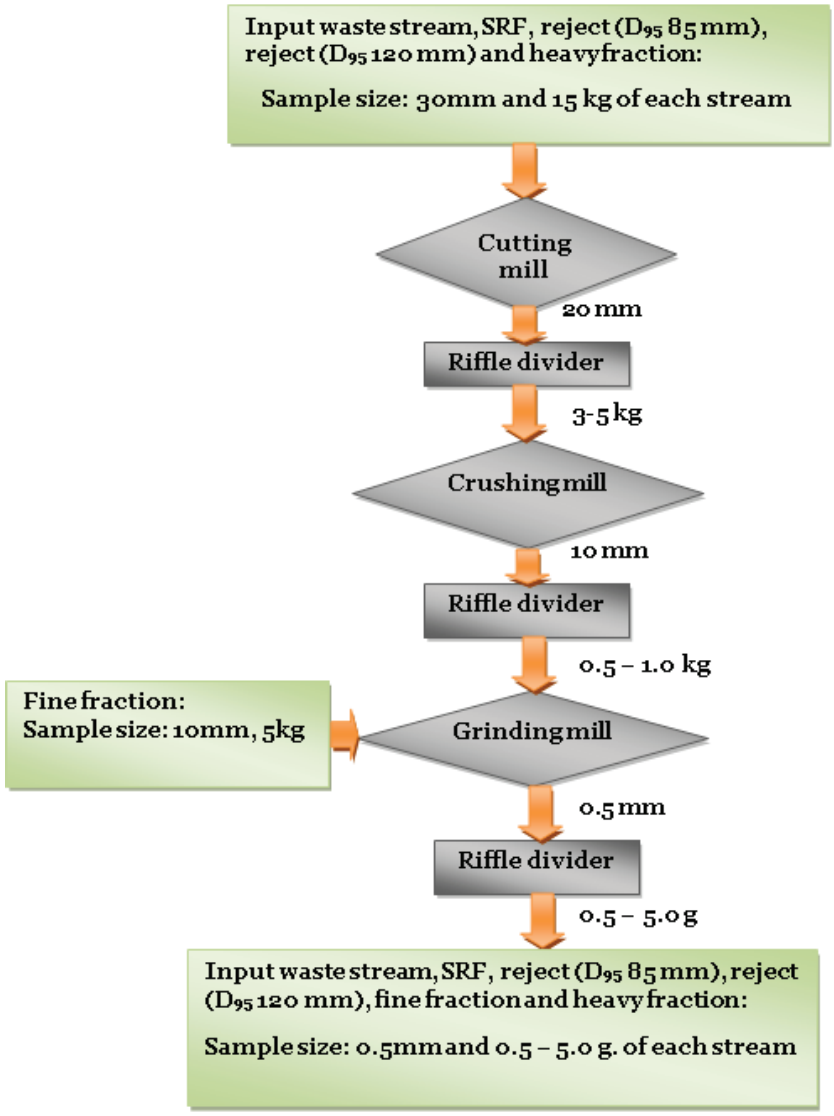


Figure 4: Procedure of sample preparation of process streams in the laboratory [Paper I]

2.5 Sample preparation of waste components

The input waste streams (i.e. C&IW, C&DW and MSW) were manually sorted into their components. Sample preparation of the waste components of the input waste streams was performed by following the same procedure as described for the process streams (described in 2.4.2.). The components of the input waste streams were paper & cardboard, wood, plastic (soft), plastic (hard), textile, rubber, foam and fines.

2.6 Laboratory analysis of process streams and waste components

Prepared samples of input and output streams and the components of input waste streams were comprehensively analysed in the laboratory for their proximate and ultimate analysis and elemental analysis. In the laboratory, standard analysis methods were applied for each sample analysis test. The standard methods used for the laboratory analysis of samples of process streams and waste components are listed in Table 3.

Table 3. Standard methods used for the laboratory analysis of samples of process streams and waste components [Paper II and Paper III]

Analysis parameter	Standard method
Moisture	CEN/TS 15414-2
Ash content (550 °C)	EN 15403
Volatile matter	EN 15402
Biomass content	EN 15440
Heating value	EN 15400
C, H, N, ($O_{calculated}$)	EN 15407
S	ASTM D 4239 (mod).
Halogen (Cl, Br, F)	SFS-EN ISO 10304-1
Major elements/Heavy metals	SFS-EN ISO11885
Minor elements/Trace elements	SFS-EN ISO 17294-2

Microwave assisted dissolution method was used for SRF samples with different acids/chemicals i.e. hydrogen peroxide (H_2O_2) + nitroxyl (HNO) + hydrofluoric acid (HF) + boric acid (H_3BO_3). Laboratory analysis of major elements, minor elements and halogen was based on elementary analysis: inductively coupled plasma optical emission spectrometry (ICP-OES), inductively coupled plasma mass spectrometry (ICP-MS) respectively.

2.7 Compositional analysis of process streams

Composition of streams means their breakdown by type of material contained (such as paper & cardboard, wood, plastic, textile etc.). The composition of the input and output streams was determined by means of the manual sorting of each stream. Combined samples (see Table 2) of each stream were sorted manually into its components. The waste components were paper & cardboard, plastic (soft), plastic (hard), wood, biowaste (food waste), textile, ferrous metal, non-ferrous metal, foam, rubber, glass and stone/rock.

2.8 Material flow analysis (MFA) approach

The mass flow of polluting and potentially toxic elements (PTEs) from the input waste stream into the output streams was examined and evaluated by means of the elemental balance of the SRF production process. The elemental balance of SRF production was calculated for chlorine (Cl), lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg). The material flow analysis (MFA) approach was applied to calculate the elemental balance of SRF production. In the process evaluation of waste treatment, MFA is an attractive decision-support tool. MFA is a systematic assessment of the flow of materials within a system defined in space and time. In a waste treatment process, the whereabouts of hazardous chemicals can be determined based on an exact accounting of all substance flows. (Rotter et al., 2004). Methodology for the assessment of waste treatment processes based on the analysis of material flows has been described and published (Rechberger, 2001; Bruner and Rechberger, 2004). The SRF production process evaluated in order to establish the elemental balance by using MFA is shown in Figure 5.

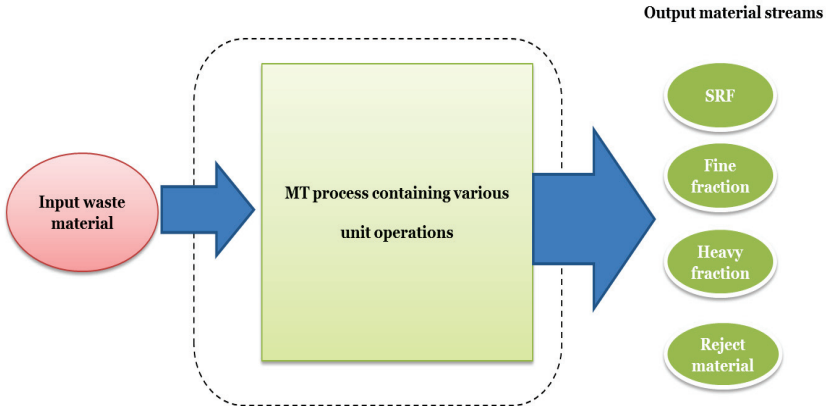


Figure 5: Flow balance of MT process to produce SRF [Paper II]

In the MT-based waste sorting plant, the input waste material was only subjected to mechanical separation and no material transformation (i.e. physical or chemical changes in material) and moreover, the system did not store any material within it. All the input waste material was recovered (with negligible material loss) in the form of output streams. Based on the law of mass conservation, the input mass balance of element(s) was calculated from the sum of its mass in the output streams. The elemental balance was calculated using Eq. (1).

$$X_{input,s} = m_{input} * C_{input,s} = \sum_{i=1}^{k}(m_{pi} * C_{pi,s}) \quad (1)$$

Where X is the load of the element; c is the concentration of the element; m refers to the mass of the stream; pi refers to the output i; (s) refers to the element; and k the number of outputs.

The energy balance of the SRF production process was also calculated based on the MFA approach. The energy flow balance in the process streams of the SRF production process was based on the law of energy conservation; the input energy balance was calculated from the sum of the energy content of the output streams.

The specific load contribution of elements in the components of unsorted waste streams (i.e. input waste streams of C&IW, C&DW and MSW) was determined from the composition of input waste streams and elemental analysis of the waste components. The specific load of an element by a waste component in unsorted/input waste stream was calculated by multiplying the mass fraction of a certain component in the input waste stream with the concentration of the element in the waste component of the input waste stream.

Determination of the uncertainty aspects in sampling (sampling of streams from the SRF production plant) and sub-sampling (sample preparation of process streams for laboratory analysis) required very extensive sampling quantities and was not feasible for this scale of research and therefore, could not be addressed for this work. Determination of the precision of sampling and subsampling methods for SRF has been presented in detail (QUOVADIS). The confidence in sampling and measured and calculated values (for elemental analysis of waste components, specific load contribution calculations and elemental balances in the SRF production process) was based on the fact that the sampling of process streams from the SRF production plant and sample preparation for laboratory analysis were performed according to CEN standard methods (EN 15442; EN 15443).

In this work, the mass, material, energy and elemental balances are presented/shown in the form of Sankey diagrams. Sankey diagrams are suitable way to visualize the material and energy balance, in which the width of arrow is proportional to the quantity of flow.

3 Material and energy balance of SRF production from commercial and industrial waste

(Papers I and II)

This chapter presents the material and energy balance of SRF production from commercial and industrial waste (C&IW). In an industrial-scale experimental campaign, SRF was produced from a batch of 79 tonnes of C&IW. Material and energy balances are presented in terms of mass, energy, material (Paper I) and elemental (Paper II) balances of commercial-scale SRF production. Mass balance means the overall mass flow of the input waste stream into the output streams, whereas material balance here refers to the mass balance of the components of the input waste (i.e. paper & cardboard, wood, plastic (soft), plastic (hard), textile and rubber) in the output streams of SRF production. Detailed proximate & ultimate analysis (Paper I) and elemental analysis (Paper II) of the input and output streams and waste components are described. Elemental analysis includes analysis of halogen, heavy metals, major and minor/trace elements. The composition of the input and output streams and the energy consumed to process C&IW in the MT waste sorting plant to produce SRF are also presented (Paper I). Based on the elemental analysis of waste components, the potential sources of polluting and potentially toxic elements (PTEs) were traced and identified (Paper II). The specific elemental load contributed by different waste components was calculated (Paper II) based on the elemental analysis of waste components and composition of C&IW. The whole of this work is presented in appended Papers I and II.

3.1 Proximate & ultimate and elemental analysis of process streams and waste components: SRF produced from C&IW (Paper I & Paper II)

The input and output streams produced in SRF production and the waste components of C&IW were analysed in the laboratory for their proximate & ultimate (Paper I) and elemental analysis (Paper II). The input and output streams included: C&IW (input waste stream), SRF, reject material and fine fraction. Metal (ferrous/non-ferrous) streams were not included in the laboratory analysis. The heavy fraction stream of SRF production was also not included in the laboratory analysis as it contained only 0.4 wt. % of the input material and mainly consisted of inert material (i.e. stones and rocks etc.). The waste components of C&IW included: paper & cardboard, plastic (hard), plastic (soft), textile, wood, rubber, foam and fines. Plastic (hard) and plastic (soft) were separated based on their physical/apparent hardness and softness, for example plastic (soft) mainly included plastic bags etc. and plastic (hard) consisted of hard plastic material (waste components).

The net calorific value (NCV) of SRF produced from C&IW was measured as 18.0 MJ/kg, a.r. and 25.0 MJ/kg, d. This high calorific value of SRF was due to the high mass fraction of plastics in it. The SRF contained 40.5 wt. % of plastics (soft and hard). The NCV of SRF (i.e. 23.56 MJ/kg, d.) was reported in the literature (Vainikka et al., 2011). Plastic components were reported (Rotter et al., 2004; Velis et al., 2011; Nasrullah et al., 2015c) as the major contributor to the calorific value of SRF. The NCV of C&IW and reject material was measured as 13.0 MJ/kg, a.r. and 11.6 MJ/kg, a.r., respectively. C&IW and the reject material stream contained a considerable mass fraction of waste components containing high calorific value, such as plastic, rubber and textile. The ash content (550 °C) of SRF was measured as 12.5 wt. %. Among the SRF production streams, the fine fraction was measured to contain the highest moisture and ash content (550 °C), i.e. 44.5 wt. % and 48.0 wt. %. The high ash content of the fine fraction stream was due to the high mass fraction of inert material (stone/sand/concrete, glass etc.) in it.

Among the components of C&IW, plastic (soft), plastic (hard), foam and textile were measured to have NCV of 37.0 MJ/kg, d. 35.0 MJ/kg, d. 27.3 MJ/kg, d. and 24.8 MJ/kg, d., respectively. The NCV of wood was measured as 18.6 MJ/kg, d. The ash content (550 °C) of rubber material was measured as 23.0 wt. %. Paper & cardboard and textile had a 13.0 wt. % and 10.4 wt. % ash content (550 °C), respectively. Among the waste components, wood was measured to contain the lowest ash content (550 °C), i.e. 1.6 wt. %. The Laboratory analysis results (Paper I) of process streams and components of C&IW taken from the SRF production plant are given in Table 4.

The elemental analysis (Paper II) of the waste components of C&IW and input and output streams are given in Table 5 and Table 6, respectively. In the reject material stream, the chlorine (Cl) content was measured as 1.2 wt. %, which was higher than measured in other output streams. This was due to the high mass fraction of PVC plastic and highly chlorinated rubber material sorted by NIR sorting technology into the reject material stream. The SRF stream was measured to contain 0.6 wt. % of chlorine (Cl). The SRF contained a significant mass fraction of plastic (hard), i.e. 16.5 wt. %. In plastic (hard), the chlorine content was measured as 3.0 wt. %. The chlorine content of SRF could be related to the high contribution of plastic (hard) it contained. Among the waste components, rubber and plastic (hard) were measured to contain 8.0 wt. % and 3.0 wt. % chlorine (Cl), respectively, which was higher than measured in other components. Among waste components, a high chlorine content has been reported (Rotter et al., 2004; Roos and Peters 2007; Velis et al., 2013; Nasrullah et al., 2015b; Nasrullah et al., 2015c) in plastic, rubber, leather and shoes. The reject material was measured to contain 0.3 wt. % of bromine (Br), which was considerably higher than that measured in other output streams. Among the waste components, textile was measured to contain a far higher bromine content than other components. Textile was measured to contain 0.06 wt. % of bromine (Br). It was found that, in textile especially, the synthetic textile component contained higher bromine content than normal textile

(fibrous-based). The antimony (Sb) content in the reject material was measured as high as 1160 mg/kg. Textile was also measured to contain a significantly higher antimony content than other waste components, i.e. 360 mg/kg. The reject stream contained a sizeable mass fraction of textile, i.e. 9.2 wt. %, which was higher than in other process streams, causing its higher bromine and antimony content. Flame-retardant textiles were reported (Vainikka et al., 2011; Vainikka and Hupa, 2012; Wua et al., 2014) to be one of the main sources of bromine (Br) in waste components. The fine fraction and reject material were measured to contain 9.8 mg/kg and 7.0 mg/kg of arsenic (As) content, respectively. Among the waste components, textile was measured to have a comparatively higher arsenic (As) content than the others. Rubber material clearly had a higher cadmium (Cd) content, i.e. 11.0 mg/kg, than the other components. Lead (Pb) was comparatively measured to be homogeneously distributed among the reject material, fine fraction and SRF. Plastic (hard) was measured to contain 400 mg/kg of lead (Pb), which was higher than the other waste components. A higher mercury (Hg) content was measured in the fine fraction compared with other output streams, i.e. 0.4 mg/kg. Among the waste components, textile and foam were measured to contain 0.2 mg/kg of mercury (Hg) each.

Among the output streams of SRF production, the reject material was measured (Paper II) to contain a higher concentration of polluting and PTEs, especially chlorine (Cl), bromine (Br), antimony (Sb) and cadmium (Cd) as compared with other output streams (Table 6). After the reject material, the fine fraction was found to be the second most polluting stream, especially as it was measured to contain a higher concentration of mercury (Hg), lead (Pb) and arsenic (As) than measured in other output streams (Table 6). The fine fraction was also measured to have a higher moisture and ash content than other streams (Table 4). Among the components of C&IW (input waste stream), rubber, plastic (hard) and textile (to a certain extent, especially synthetic type textile) were identified (Table 5) as potential sources of polluting and PTEs, especially in terms of chlorine (Cl), arsenic (As), cadmium (Cd) and lead (Pb).

Table 4: Laboratory analysis results of process streams and components of C&IW taken from the SRF production plant (mean value of three laboratory test sub-samples) (Paper I)

Parameters	Moist. cont.	Ash cont. 550°C	C	H	N	S	$O_{calc.}$	NCV[a]	GCV[b]	NCV[a]
stream	wt. %	wt. %	wt.%	wt. %	wt. %	wt. %	wt. %	MJ/kg (a.r.)[c]	MJ/kg (d.)[d]	MJ/kg (d.)[d]
C&IW	26.5	16.6	48.0	7.0	0.6	0.2	18.0	13.0	19.8	18.5
SRF	25.0	12.5	57.4	8.0	0.5	0.3	17.8	18.0	26.6	25.0
Reject	26.0	23.0	41.0	5.8	1.0	0.3	20.8	11.6	18.8	16.6
Fine fraction	44.5	48.0	29.6	4.0	1.2	0.8	16.0	5.5	12.6	12.0
Components of C&IW										
Paper & card	n.a.	13.0	42.5	5.6	0.4	0.1	38.0	n.a.	17.3	16.0
Plastic (soft)[e]	n.a.	10.3	74.6	12.0	0.3	0.2	2.3	n.a.	39.5	37.0
Plastic (hard)[e]	n.a.	6.0	74.4	11.4	0.3	0.1	5.0	n.a.	37.4	35.0
Textile	n.a.	10.4	57.4	7.6	1.8	0.24	21.3	n.a.	26.5	24.8
Wood	n.a.	1.6	49.0	6.2	0.8	<0.02	42.2	n.a.	20.0	18.6
Rubber	n.a.	23.0	48.0	5.2	1.0	0.5	14.3	n.a.	21.0	20.0
Foam	n.a.	5.0	62.5	8.4	4.0	0.1	19.8	n.a.	29.0	27.3
Fines	n.a.	54.4	26.8	3.5	1.3	1.0	22.6	n.a.	10.6	9.8

[a] NCV: net calorific value
[b] GCV; gross calorific value
[c] (a.r.): as-received basis of material
[d] (d.): dry basis of material
[e] Plastic (soft) and plastic (hard); separated on the basis of their physical hardness
n.a.: not available

Table 5: Elemental analysis of components of commercial and industrial waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper II)

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood	Fines
1	Cl	wt %, d	0.2	3.0	0.14	1.0	8.0	0.2	0.075	0.4
2	Br	wt %, d	<0.001	0.002	<0.001	0.06	<0.001	0.002	<0.001	0.002
3	F	wt %, d	0.002	0.002	0.002	0.003	0.002	0.002	<0.001	0.007
4	S	wt %, d	0.1	0.08	0.08	0.2	0.5	0.1	<0.02	1.0
5	Na	mg/kg, d	2300	820	2800	2300	1100	1000	780	26400
6	K	mg/kg, d	1100	570	2000	1700	1200	1100	990	9700
7	Ca	mg/kg, d	39500	16200	14800	21100	75400	14200	2500	66800
8	Mg	mg/kg, d	1700	2200	1400	860	11300	860	280	6000
9	P	mg/kg, d	230	240	550	330	420	290	120	1500
10	Al	mg/kg, d	11400	3300	4600	2600	2900	1500	510	23200
11	Si	mg/kg, d	9000	6100	16300	9400	17500	5300	1700	57100
12	Fe	mg/kg, d	1100	1000	8000	1700	1900	1500	690	19400
13	Ti	mg/kg, d	920	3500	4000	1000	4400	740	330	10200
14	Cr	mg/kg, d	12	80	30	360	1300	20	7.3	270
15	Cu	mg/kg, d	20	3.6	80	21	1400	16	5.0	500
16	Mn	mg/kg, d	48	60	76	120	50	32	75	260
17	Ni	mg/kg, d	6.0	28	15	12	20	7.7	5.7	150
18	Zn	mg/kg, d	88	370	420	150	5500	260	80	1400
19	Sb	mg/kg, d	4.4	84	12	360	30	40	1.2	23
20	As	mg/kg, d	<0.5	0.6	1.0	2.0	1.2	1.6	<0.5	5.5
21	Ba	mg/kg, d	55	240	280	120	1300	420	31.0	1300
22	Cd	mg/kg, d	0.1	2.7	0.2	0.2	11.0	0.1	0.16	1.3
23	Co	mg/kg, d	2.0	3.3	180	31.0	2.0	2.0	0.8	12.0
24	Pb	mg/kg, d	9.5	400	76.0	17.0	250	16.0	3.0	320
25	Mo	mg/kg, d	0.7	3.7	3.0	3.5	2.2	4.2	<0.5	1300
26	Se	mg/kg, d	<0.5	0.5	<0.5	0.5	0.6	0.5	<0.5	3.0
27	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
28	Sn	mg/kg, d	2.0	13.0	9.8	5.3	100	260	0.6	36
29	V	mg/kg, d	3.7	1.8	4.2	2.7	17.0	2.6	0.7	18.0
30	Hg	mg/kg, d	<0.05	0.05	0.4	0.2	0.08	0.2	<0.05	0.3

Table 6: Elemental analysis of input and output streams produced in SRF production: SRF produced from commercial and industrial waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper II)

#	Element	Unit	Input waste stream	Reject material stream	Fine fraction stream	SRF stream
1	Cl	wt %, d	0.6	1.2	0.4	0.6
2	F	wt %, d	0.007	0.008	0.01	0.01
3	Br	wt %, d	0.005	0.3	0.006	0.003
4	S	wt %, d	0.2	0.3	0.8	0.3
5	Na	mg/kg, d	2990	4450	23300	3460
6	K	mg/kg, d	2150	2900	8800	2175
7	Ca	mg/kg, d	18530	39540	57000	36260
8	Mg	mg/kg, d	1590	2420	5200	1480
9	P	mg/kg, d	870	775	1600	960
10	Al	mg/kg, d	7300	14230	19900	8200
11	Si	mg/kg, d	22180	25020	58600	18870
12	Fe	mg/kg, d	4400	4160	12000	4840
13	Ti	mg/kg, d	3090	2130	5700	3160
14	Cr	mg/kg, d	290	80	190	50
15	Cu	mg/kg, d	5800	1015	330	375
16	Mn	mg/kg, d	110	100	210	80
17	Ni	mg/kg, d	20	45	95	20
18	Zn	mg/kg, d	4120	540	1000	335
19	Sb	mg/kg, d	7.2	1160	30	50
20	As	mg/kg, d	5.0	7.0	9.8	1.8
21	Ba	mg/kg, d	290	415	880	290
22	Cd	mg/kg, d	1.2	1.5	1.0	0.6
23	Co	mg/kg, d	2.4	4.8	10	3.6
24	Pb	mg/kg, d	90	150	235	120
25	Mo	mg/kg, d	3.0	4.3	10	3.6
26	Se	mg/kg, d	0.5	<0.5	1.7	0.5
27	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5
28	Sn	mg/kg, d	8.8	34	25	18.8
29	V	mg/kg, d	6.0	7.7	16	5.3
30	Hg	mg/kg, d	0.1	0.2	0.4	0.1

3.2 Mass, energy and material balances of SRF production: SRF produced from C&IW (Paper I)

The mass balance of the SRF production process was established for a batch of 79 tonnes of C&IW fed to MT waste sorting plant to produce SRF. Based on the unit operations/sorting techniques used in the MT plant, the input waste stream (C&IW) was divided into various output streams: SRF, fine fraction, heavy fraction, reject material, ferrous metal and non-ferrous metal. All the output streams were weighed. All the input waste material was recovered in the form of output streams with a negligible amount of difference. Of the total input C&IW material enetring the process (by weight) , 62 % of the material was recovered in the form of SRF, 5 % in the form of metals, 21 % was separated as as reject material, 11.6 % as fine fractionand 0.4 % as heavy fraction. The mass balance of SRF production from C&IW is shown in Figure 6.

The energy flow balance from the input waste stream (C&IW) into the output streams of SRF production was calculated based on the material flow analysis (MFA) approach (described in Section 2.8). By applying the law of energy conservation, the input energy balance was calculated from the sum of the energy content of the output streams. The energy content of the output streams was calculated by multiplying their heating values (NCV, MJ/kg) (given in Table 4) by their respective total mass (from the mass balance of SRF production as shown in Figure 6) for both the wet and dry basis of material. The energy content of the heavy fraction stream was calculated from its composition and the heating values of waste components it contained (given in Table 4). The difference between the measured and calculated values of the input energy content is calculated as an error value. In the SRF production, energy recovered in the form of SRF was 75% and 78% of the total input energy for wet and dry basis of material respectively. The energy connected with the metal streams (ferrous metal and nonferrous metal) was due to a very minor amount of combustibles (such as paper & cardboard, plastic, foam and wood) in these streams not due to the metals, as the energy content of metals was considered to be zero (Biffaward, 2003). The energy content of the reject material and fine fraction was a result of the considerable mass fraction of components such as plastics, rubber, paper and cardboard and wood (to a smaller extent) in these streams. The energy flow balance in the process streams of SRF production from C&IW on wet and dry basis is shown in Figure 7.

The energy consumed for a process batch of 79 tonnes of C&IW at the MT waste sorting plant to produce SRF was calculated in terms of in-plant operations and out-plant operations. In-plant operations included unit operations/sorting techniques used in the MT plant such as shredding, screening, magnetic/eddy current separation, air classifiers, NIR sorting units, conveyor belts, a dust extraction system and material handling vehicles (wheel loaders and excavators). Out-plant operations included the logistical means involved in collecting C&IW from its collection points and delivering it to the MT plant; out-plant operations also included the transportation for delivering the output

streams (SRF, metals, reject material, fine and heavy fraction) to the customers' premises. The energy consumed per unit tonne of feed (input waste stream of C&IW) was calculated (Paper I) as 60 kWh and 130 kWh for in-plant operations and out-plant operations respectively.

The material balance of SRF production included the mass balance of waste components from the input waste stream into the various output streams. Waste components for which material balances were calculated were paper & cardboard, wood, plastic (soft), plastic (hard), textile and rubber. In order to optimize the plant configuration to produce SRF with predictable and specified quality, the flow of waste components (paper, plastics, wood, etc.) through an SRF production facility needs to be understood (Velis et al., 2013). The calculation of the material balance (Paper I) was based on the composition of the input and output streams (see Section 3.3.) and the overall mass balance of SRF production (see Figure 6).

The material balance showed (Paper I) that the recovery of plastic (soft) from input waste into the SRF stream was on the high side. Of the total input plastic (soft), 88 wt. % was recovered in the SRF. On the other hand, the recovery of paper & cardboard and wood components was not as high as that of plastic (soft). Of the total paper & cardboard and wood entering the process, 72 wt. % and 60 wt. %, respectively, were recovered in the SRF. A sizeable mass fraction of paper & cardboard and wood was found in the reject material stream, which was supposed to be in the SRF stream. It was found that the majority of the paper & cardboard and wood components found in the reject material were highly moist (> 25 wt. %), large in particle size (> 200 mm) or irregular in shape (paper in rolled/bundled form). Primary shredding of input waste material could have caused the cross-contamination of moisture content to paper and cardboard from other components with a high moisture content. The recovery of textile components was also comparatively on the low side. Of the total textile entering the process, 58 wt. % was recovered in the SRF and 21 wt. % was found in the reject material. As described in the elemental analysis of waste components (Table 5), textile was measured to contain 1.0 wt. % of chlorine (Cl). Textile was also measured to contain a much higher concentration of bromine (Br) and antimony (Sb) as compared with other waste components. Some textile components in the reject material were found to have a high moisture (> 25 wt. %) content and to be larger in particle size (> 200 mm). Of the total input plastic (hard), 70 wt. % was recovered in the SRF and 20 wt. % was found in the reject material. A major fraction of plastic (hard) found in the reject material contained PVC plastics (highly chlorinated). In the case of rubber, the majority was separated into the reject material. Of the total rubber entering the process, 56 wt. % was found in the reject material. Rubber material found in the reject material was measured to have a high chlorine content. As described in the elemental analysis of C&IW components, among the waste components rubber was measured to have the highest chlorine content, i.e. 8.0 wt. % (Table 5).

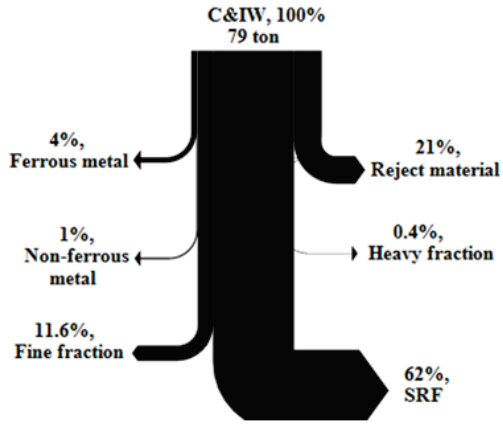


Figure 6: Mass balance of SRF production from C&IW (basis of material) (Paper I)

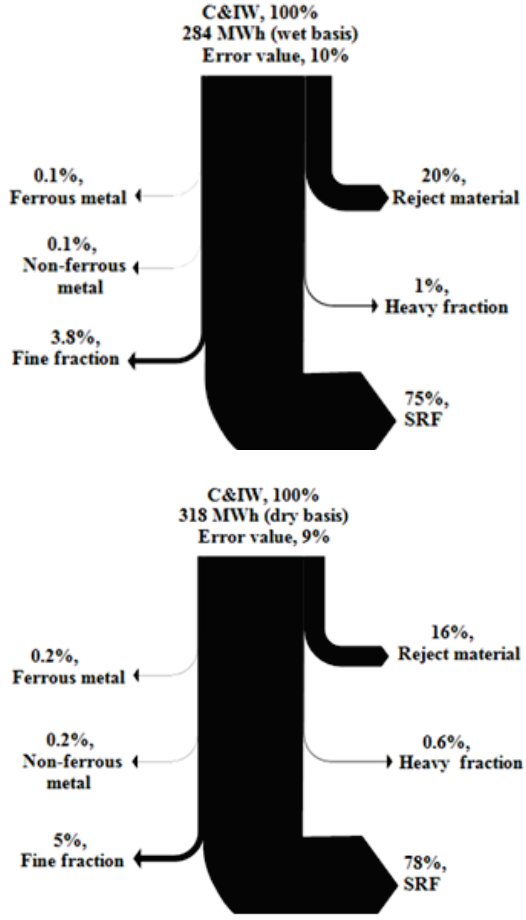


Figure 7: Energy flow balance in process streams of SRF production from C&IW (Paper I)

The use of near-infrared (NIR) technology in the SRF production process proved very helpful in separating waste components such as PVC plastic, rubber and to some extent textiles (especially the synthetic type) containing polluting elements (especially chlorine) from the input waste stream into the reject material. In the newly built mechanical biological treatment (MBT) plants, the use of NIR technology has reduced the total chlorine content of SRF by removing highly chlorinated plastic components (Schirmer et al., 2007). The material balance of paper & cardboard, wood, plastic (soft), plastic (hard), textile and rubber for SRF production from C&IW is presented in Paper I, which describes and explains the recovery of input waste components into SRF.

3.3 Composition of input and output streams

The composition of streams means their breakdown by type of material contained (such as paper & cardboard, wood, plastic, textile etc.). The composition of the input and output streams was determined by manual sorting of their respective combined samples (Table 2).

The C&IW (input waste stream) mainly contained paper & cardboard and plastics. The C&IW contained 31 wt. % of paper & cardboard and 31.6 wt. % of plastics (hard and soft). In the SRF produced from C&IW, the mass fraction of paper & cardboard and plastics was further enriched. The SRF contained 35.6 wt. % of paper & cardboard and 40.5 wt. % of plastics (hard and soft) and 8.5 wt. % of textile as major components. Paper and cardboard has been reported (Velis et al., 2011; Nasrullah et al., 2015a) as a dominant fraction of SRF. In this SRF, the mass fraction of plastic (soft) was higher than that of plastic (hard). In the reject material, inert material (stone/rock and glass) and fines were the major fractions, i.e. 28.5 wt. % and 17.0 wt. %, respectively. There was also a significant mass fraction of plastic (hard) and rubber in the reject material, i.e. 14.0 wt. % and 6.8 wt. %, respectively. In the reject material, the plastic (hard) was mainly PVC plastic and the rubber was highly chlorinated. The heavy fraction contained mainly stone/rock (heavy particles). The composition of input and output streams produced in SRF production from C&IW is presented and discussed in Paper I.

The energy-based composition of SRF was calculated (Paper I) based on the SRF composition (on mass basis) and net calorific values of its components (given in Table 4). It was calculated by multiplying the mass fraction of components of SRF by their respective net calorific values. The major energy content of SRF was found to be contained in plastic (soft), plastic (hard) and paper & cardboard. Plastics (soft and hard) and paper & cardboard in the SRF stream accounted for 59.6% and 23.1% of the total energy content of SRF respectively. The energy-based composition of SRF produced from C&IW is shown in Figure 8.

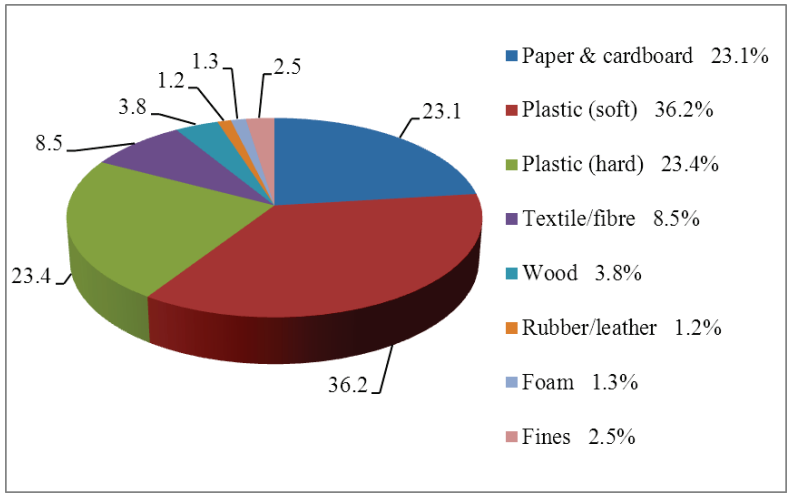


Figure 8: Energy-based composition of SRF produced from C&IW [Paper I]

3.4 Elemental balance of SRF production from C&IW

The elemental balance of SRF production was calculated [Paper II] for polluting and PTEs; chlorine (Cl), arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg). The mass flow of polluting and PTEs from the input waste stream into the output streams was examined and evaluated by means of an elemental balance of SRF production. The elemental balance of SRF production from C&IW is shown in Figure 9.

In the elemental balance of SRF production, of the chlorine (Cl) and lead (Pb) content entering the process, 60 wt. % and 58 wt. % respectively were found in the SRF stream and 40 wt. % and 42 wt. % respectively were separated in other output streams. Of the cadmium (Cd) content entering the process, 54 wt. % was separated in other output streams and 46 wt. % was found in the SRF. Of the mercury (Hg) content entering the process, 55 wt. % was separated in other output streams, while 45 wt. %, was found in the SRF. In the case of arsenic (As), 68 wt. % of the content entering the process was separated in other output streams and 32 wt. % was found in the SRF (Figure 9). Here, the term 'other output streams' refers to those besides SRF, i.e. reject material, fine fraction and heavy fraction.

Among the unit operations used in the MT process, the air classifier and NIR sorting unit were the most effective in determining the quality of SRF. The major distribution of combustible components (paper & cardboard, wood, non-PVC plastics, suitable textile and other components) and non-suitable components (PVC plastic, highly chlorinated rubber and waste components containing high concentration of PTEs) into SRF and reject material was performed by the air classifier and NIR sorting units.

As described earlier, the reject material stream was found to contain a significant mass fraction of combustible components (especially paper & cardboard

and wood and to a certain extent textile), which were supposed to be in the SRF. Waste components (paper & cardboard and wood and to a certain extent textile) found in the reject material were either large in particle size (> 200 mm), highly moist (> 25 wt. %) or irregular in shape (for example paper & cardboard and textile in bundled form). For these combustible components, their heavy weight/density (due to high moisture, bundled form etc.) and larger particle size could be the reason for not being sorted properly by the air classifier and NIR sorting unit into the SRF stream. As shown in the elemental analysis of waste components (Table 5), paper & cardboard and wood contained the least amount of polluting and PTEs as compared with other waste components. Therefore, the recovery of paper & cardboard and wood (found in the reject material) into the SRF stream could have effectively reduced the polluting elements and PTEs content of the SRF.

On the other hand, rubber, plastic (hard) and textile (to a certain extent, especially synthetic textile) were measured to contain the highest concentration of polluting and PTEs among the waste components of C&IW (Table 5). During the operation of the air classifier, some lightweight components of rubber, plastic (hard) and textile (especially synthetic type) containing a high concentration of polluting and PTEs could have been sorted/separated and put into the SRF stream. The sorting of these components into the SRF stream could have caused a higher mass flow of chlorine (Cl), cadmium (Cd), lead (Pb) and mercury (Hg) into the SRF stream as compared with the other output streams (Figure 9). Making one pass/check of NIR sorting (with negative sorting) to the air-classified fraction before the components entered the SRF stream could have prevented certain undesired components of rubber, plastic (hard) and textile (to a certain extent, especially synthetic textile) from entering the SRF stream and reduced the concentration of polluting and PTEs in the SRF.

The flow rate of the input waste stream was also observed as a very important process parameter, which might have affected (negatively) the proper sorting of incoming waste components into the relevant output streams. Sudden/quick/non-steady peaks of material passing from the unit operations might have affected (in a negative way) the operating performance of the unit operations (especially the air classifier and NIR sorting unit) and certain desirable components (especially paper & cardboard and wood) missed separation/sorting (by the air classifier or/and NIR sorting unit) into the SRF and ended up in the reject material. It is important to balance the mass flows of the plant by steady feeding of input waste at the start of the process and adjusting processes so that the mass flows of material pass from the processes (unit operations) steadily and as per the designed capacities of the equipment. In this way, the issue of too many or sudden peaks of material coming to any of the sorting processes could be addressed. Regular maintenance checks/inspection are also vital (e.g. keeping the air nozzles of the NIR units clean) to make sure that the machines are functioning properly and that the set-ups are correct.

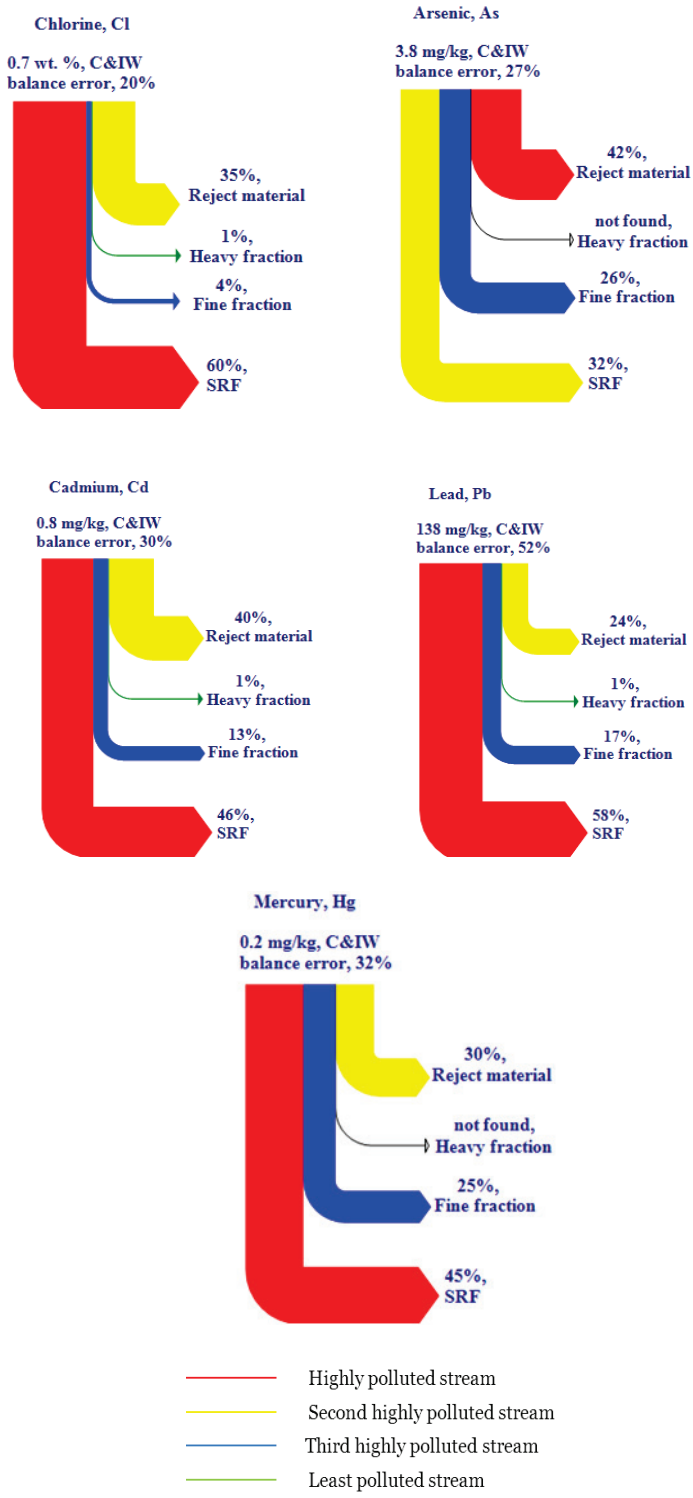


Figure 9: Elemental balance of SRF production from commercial and industrial waste [Paper II]

The specific load contribution of polluting elements and PTEs by waste component in unsorted C&IW was calculated [Paper II] based on the composition of the C&IW and elemental analysis of the waste components. To calculate the specific load of an element contributed by waste component in unsorted C&IW (i.e. input waste stream), the mass fraction of that component in C&IW was multiplied by the concentration of the element in that component. The highest load of chlorine in unsorted C&IW was found to be contributed by plastic (hard) components. Plastic (hard) was also found to carry a higher load of lead and cadmium in C&IW as compared with other waste components.

Of the total load of chlorine, cadmium and lead in unsorted C&IW, 51%, 47% and 59%, respectively, were calculated to be carried by plastic (hard) components (Paper II). Rubber material was found to carry a 20% load of chlorine (Cl) and about 35 % of cadmium (Cd) in unsorted C&IW. Textile components were calculated to carry a considerably higher load of bromine (Br) and antimony (Sb) than other waste components, i.e. 84.6% and 64.3%, respectively, of the total load in unsorted C&IW. A higher load of arsenic (As) was carried by fines, i.e. 29% of its total load in C&IW as compared with the other waste components. The specific elemental load contribution by waste components in unsorted C&IW is shown and discussed in Paper II.

Major findings

- Of the C&IW entering the process, 62 wt. % was recovered in the form of SRF and 5 wt. % as metals (ferrous and non-ferrous). The energy recovered in the form of SRF was 75 % (on wet basis) and 78 % (on dry basis) of the total energy content of C&IW entering the process. The energy consumed to process C&IW in the MT plant to produce SRF was calculated in the forms of in-plant and out-plant operations. The energy consumed per unit tonne of feed for in-plant operations and out-plant operations was calculated as 60 kWh and 130 kWh, respectively.
- In the composition of C&IW, paper & cardboard and plastics (soft and hard) were the dominant waste components, with 31 wt. % and 31.5 wt. %, respectively. The SRF produced from C&IW was further enriched with paper & cardboard and plastics (soft and hard) containing 35.6 wt. % and 40.5 wt. %, respectively. In the SRF, the mass fraction of plastic (soft) was higher than that of plastic (hard). The reject material separated in the process mainly consisted of highly chlorinated rubber, PVC plastic and inert material (stone/rock, glass and a very small fraction of metals).
- In the elemental balance of SRF production, of the chlorine (Cl) and lead (Pb) content entering the process in the feed, 40 wt. % and 42 wt. % respectively were separated/sorted into other output streams. In the case of cadmium (Cd), 54 wt. % of the content entering the process was separated into other output streams. As for mercury (Hg), 55 wt. % of the content entering the process was separated into other output streams. In the case of arsenic (As), 68 wt. % of the content was sepa-

rated into other output streams. ‘Other output streams’ here refer to those besides SRF, i.e. reject material, fine fraction and heavy fraction.

- Among the components of C&IW, rubber and plastic (hard) were measured to contain 8.0 wt. % and 3.0 wt. % (dry basis) respectively of chlorine (Cl), which was higher than that measured in other components. Plastic (hard) was also measured to contain a higher content of lead (Pb), i.e. 400 mg/kg, d. than the other waste components. In rubber, a higher cadmium (Cd) content was measured than that in other components of C&IW. Paper and cardboard, wood, and foam were among the components containing the lowest amount of polluting elements and PTEs.
- Recovery of combustible components (especially paper & cardboard and wood) from the reject material stream into the SRF stream could have further enhance the yield of SRF and effectively reduce the content of polluting elements and PTEs in the SRF.

4 Material and energy balance of SRF production from construction and demolition waste

(Papers III and IV)

This chapter deals with the material and energy balance of SRF production from construction and demolition waste (C&DW). The SRF was produced on industrial scale from a batch of 74 tonnes of C&DW through mechanical treatment (MT). The results presented here comprised the proximate & ultimate analysis (Paper III) and elemental analysis (Paper IV) of the input and output streams in SRF production, the elemental analysis (Paper IV) of the components of C&DW, the composition of streams and the mass, energy, material (Paper III) and elemental balances (Paper IV) of SRF production. The mass flow of polluting elements and PTEs was calculated (Paper IV) in terms of the elemental balance of SRF production. The potential source of polluting elements and PTEs in C&DW were identified (Paper IV). The whole of this work is presented in appended Papers III and IV.

4.1 Proximate & ultimate and elemental analysis of process streams and waste components: SRF produced from C&D waste (Paper III and Paper IV)

The proximate & ultimate (Paper III) and elemental analysis (Paper IV) of the input and output streams in SRF production from C&DW were performed in the laboratory. In the elemental analysis (Paper IV), the concentration of halogen, heavy metals, and major and minor/trace elements was measured. Here, the input stream was the C&DW used to produce SRF, and the output streams included SRF, reject material, fine fraction and heavy fraction. Metals in each stream were excluded from laboratory analysis.

The results of the laboratory analysis of the streams (input and output) produced in SRF production from construction and demolition waste are given in Table 7. The SRF produced from C&DW was measured to contain an NCV of 18.0 MJ/kg, a.r. basis and 20.0 MJ/kg, d. basis. The dominant energy fraction of SRF was due to the high mass fraction of wood, plastics and paper & cardboard it contained. The SRF was measured to have 66.7 wt. % of bio carbon from the total carbon content. The majority of the bio carbon in the SRF was due to the wood fraction it contained. The moisture content and ash content (550 °C) of SRF were measured as 16.5 wt. % and 9.0 wt. %, respectively. C&D waste (input waste stream) was measured to have an NCV of 9.8 MJ/kg, a.r. and 11.0 MJ/kg, d. The ash content (550 °C) of C&D waste was measured as high as 46.8 wt. %, which was due to the high mass fraction of building material (inert material) in it. In the composition of C&D waste, the mass fraction of building material and fines (fines mainly contained fine particles of building material as well) was 14.2 wt. % and 16.6 wt. %, respectively. The high ash content (550 °C) of the fine fraction and heavy fraction streams, i.e. 78.8 wt. %

and 65.6 wt. %, was also due to the very high mass fraction of building material (inert material) in these streams.

Table 7: Laboratory analysis results of process streams in SRF production from construction and demolition waste (mean value of three laboratory test sub-samples) (Paper III)

Process Streams	Moist cont. wt%	Ash 550°C wt%	Volat. matter wt%	Bio[a] cont. wt%	C (d.) wt%	H (d.) wt%	N (d.) wt%	S (d.) wt%	$O_{calc.}$ (d.) wt%	NCV (a.r.)[d] MJ/kg	NCV (d.)[e] MJ/kg
C&DW	14.0	46.8	n.a.	n.a.	30.0	4.0	0.5	0.7	17	9.8	11.0
SRF	16.5	9.0	76.6	66.7	50.0	6.4	1.0	0.3	31.6	18.0	20.0
Reject	12.0	47.2	n.a.	n.a.	31.2	3.8	0.6	0.7	16.2	10.0	12.0
Fine f.[b]	23.6	78.8	n.a.	n.a.	12.0	1.3	0.4	2.8	4.8	2.5	4.0
Heavy f[c]	10.4	65.6	n.a.	n.a.	20.0	2.6	0.5	0.3	13.2	6.5	7.6

a Bio. Cont: biomass content in % bio carbon
b Fine f: Fine fraction stream
c Heavy f: Heavy fraction stream
d (a.r.): as-received basis of material
e (d.): dry basis of material

In the elemental analysis of the components of C&D waste, rubber, plastic (hard) and textile (especially synthetic type textile components) were found as potential sources of chlorine (Cl). Rubber, plastic (hard) and textile were measured to contain 7.6 wt. %, 7.0 wt. % and 3.8 wt. % of chlorine (Cl), respectively. The cadmium (Cd) content measured in rubber was also higher than that measured in other waste components. Among the waste components, foam material was measured to contain a higher bromine (Br) concentration, i.e. 0.013 wt. %. Foam material mainly comprised foam used for insulation in buildings and to some extent packaging type foam. Textile components were found to have higher arsenic (As) concentration, i.e. 12.0 mg/kg than that measured in other waste components. The lead (Pb) content measured in plastic (hard) was 880 mg/kg, which was higher than that measured in other waste components. After plastic (hard), textile was measured to contain 450 mg/kg of lead (Pb). Plastic (soft) and textile were measured to contain 0.2 mg/kg of mercury (Hg) each. The elemental analysis of components of C&D waste is given in Table 8.

Among the components of C&D waste (input waste stream), rubber, plastic (hard) and textile (especially synthetic type textile components) were identified as the potential sources of polluting elements and PTEs. Conversely, paper & cardboard, wood, plastic (soft) and foam were found to contain the least amount of polluting elements and PTEs.

An elemental analysis of the input and output streams of SRF production from C&D waste was performed (Paper IV). The reject material stream was measured to contain higher chlorine (Cl) content, i.e. 2.2 wt. % (Table 9). This

higher chlorine concentration was due to the high mass fraction of rubber and highly chlorinated plastic (PVC plastic) in the reject material stream. In the composition of reject material, the mass fraction of rubber and plastic (hard) was 15.0 wt. % and 7.4 wt. %, respectively. Apart from rubber and plastic (hard), the mass fraction of textile in the reject material was also considerable, i.e. 3.4 wt. %. Rubber, plastic (hard) and textile were the components measured to contain higher chlorine (Table 8) as compared with other components. Chlorine content measured in the SRF was 0.4 wt. % (Table 9). In the SRF high mass fraction of wood and paper & cardboard effectively reduced the overall chlorine concentration in it. In the composition of SRF, mass fraction of wood and paper & cardboard was 38 % and 22% respectively. Among the components of C&D waste, wood, plastic (soft) and paper & cardboard were measured to contain the lowest chlorine content.

Table 8: Elemental analysis of the components of construction and demolition waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper IV)

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood
1	Cl	wt %, d	0.3	7.0	0.18	3.8	7.6	0.32	0.037
2	F	wt %, d	0.004	0.013	0.006	0.006	0.006	0.003	0.001
3	Br	wt %, d	0.001	0.003	0.001	0.001	0.001	0.013	0.0002
4	Na	mg/kg, d	1700	1700	3400	3500	1200	2600	330
5	K	mg/kg, d	1000	1600	3400	3100	1500	2500	430
6	Mn	mg/kg, d	58	70	130	120	98	140	80
7	Cr	mg/kg, d	15	290	70	960	110	45	3.3
8	Cu	mg/kg, d	35	35	40	75	2300	50	3.0
9	Ni	mg/kg, d	7.0	60	30	20	90	15	1.7
10	Zn	mg/kg, d	93	890	300	460	2100	190	60
11	Sb	mg/kg, d	4.2	240	4.0	85	190	220	0.5
12	As	mg/kg, d	0.8	2.0	2.6	12	1.4	1.4	0.5
13	Cd	mg/kg, d	0.15	1.5	0.2	1.3	5.2	0.12	0.12
14	Co	mg/kg, d	1.5	4.0	5.0	4.8	4.8	4.0	0.5
15	Pb	mg/kg, d	26	880	72	450	100	15	5.4
16	Mo	mg/kg, d	2.3	15	2.3	3.0	2.4	1.0	0.5
17	Se	mg/kg, d	0.95	0.7	0.85	0.59	0.5	0.75	0.5
18	Tl	mg/kg, d	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
19	V	mg/kg, d	4.5	160	14	14	20	18	0.8
20	Hg	mg/kg, d	0.1	0.05	0.2	0.2	0.05	0.1	0.02

The fine fraction and reject material were among the output streams measured to have a higher arsenic (As) content, i.e. 13.0 mg/kg and 10.0 mg/kg, respectively (Table 9). The input waste stream of C&D waste was measured to have an arsenic concentration of 15.0 mg/kg. Among the waste components,

textile was found to have a higher concentration of arsenic (As). In the reject material, the mass fraction of textile was 3.4 wt. %. The concentration of cadmium (Cd) was found to be comparatively higher in the SRF and heavy fraction, i.e. 4.4 mg/kg and 4.0 mg/kg, respectively. Rubber material was measured to have higher cadmium content, i.e. 5.2 mg/kg, than the other waste components (Table 8). After rubber, plastic (hard) and textile were measured to contain 1.5 mg/kg and 1.3 mg/kg of cadmium, respectively. Among the output streams, the highest lead (Pb) content was measured in the reject material stream, i.e. 490 mg/kg (Table 9). In the elemental analysis, plastic (hard) was measured to have a higher lead (Pb) content than that measured in the other components of C&D waste (Table 8). The sizeable mass fraction of plastic (hard) in the reject material could have contributed to its higher lead (Pb) concentration. The SRF was measured to have the least concentration of lead (Pb) among the output streams, i.e. 42 mg/kg. The fine fraction was measured to contain a considerably higher mercury (Hg) concentration than the other streams. This could be linked with the fact that waste components with a high mercury content were shredded to a smaller particle size (< 15 mm) and sorted into the fine fraction stream by the screening process. Identification of rubber, plastic (hard) and textile (synthetic type) as a potential source of polluting elements and PTEs was in agreement with the findings of the previous research, i.e. SRF produced from C&IW (Chapter 3). The elemental analysis of the input and output streams produced in SRF production from C&D waste is given in Table 9.

From the elemental analysis of the output streams generated in SRF production from C&D waste, it was found that the reject material and fine fraction were the most contaminated in terms of carrying polluting elements and PTEs as compared with other output streams. The high recovery of wood, paper & cardboard and plastic (soft) from the input waste stream (C&D waste) into the SRF stream effectively reduced the content of polluting elements and PTEs in the SRF.

Table 9. Elemental analysis of input and output streams produced in the SRF production process: SRF produced from construction and demolition waste (mean value of three laboratory test sub-samples, dry basis of material) (Paper IV)

#	Element	Unit	Input waste	Reject material	Fine fraction	Heavy fraction	SRF
1	Cl	wt %, d	0.6	2.2	0.2	1.0	0.4
2	F	wt %, d	0.01	0.006	0.002	0.005	0.004
3	Br	wt %, d	0.005	0.008	0.002	0.001	0.003
4	S	wt %, d	0.7	0.7	2.8	0.3	0.3
5	Na	mg/kg, d	8370	8160	14400	7955	1470
6	K	mg/kg, d	6120	8060	13700	11570	1080
7	Ca	mg/kg, d	58050	56625	100800	46280	17150
8	Mg	mg/kg, d	5940	5920	8500	5150	1270
9	P	mg/kg, d	315	390	490	340	520
10	Al	mg/kg, d	18090	24280	37500	30010	4800
11	Si	mg/kg, d	51660	45000	46700	3700	12150
12	Fe	mg/kg, d	7560	10330	18200	11840	1275
13	Ti	mg/kg, d	1530	2130	2400	315	1275
14	Cr	mg/kg, d	135	180	130	100	35
15	Cu	mg/kg, d	660	950	140	715	350
16	Mn	mg/kg, d	270	250	680	280	70
17	Ni	mg/kg, d	38	68	45	22.5	8.0
18	Zn	mg/kg, d	400	595	500	310	175
19	Sb	mg/kg, d	42	70	10	5.8	84
20	As	mg/kg, d	15	10	13	4.5	6.6
21	Ba	mg/kg, d	260	645	680	390	138
22	Cd	mg/kg, d	1.5	1.0	0.6	4.0	4.4
23	Co	mg/kg, d	6.0	16	11	5.0	2.8
24	Pb	mg/kg, d	135	490	380	208	42
25	Mo	mg/kg, d	4.8	5.0	4.3	1.2	1.5
26	Se	mg/kg, d	1.8	2.2	4.0	3.0	2.7
27	Tl	mg/kg, d	0.5	0.5	0.5	0.6	0.5
28	Sn	mg/kg, d	13.5	95	26	126	14.7
29	V	mg/kg, d	23.4	38	48	33.5	4.0
30	Hg	mg/kg, d	0.2	0.08	0.7	0.05	0.2

4.2 Mass, energy and material balances of SRF production from C&D waste (Paper III)

A mass balance of SRF production was established for a batch of 74 tonnes of C&D waste used to produce SRF in an MT waste sorting plant. In the MT plant, the input C&D waste stream was classified/sorted into various output streams: SRF, fine fraction, heavy fraction, reject material, ferrous metal and non-ferrous metal. All the output streams were weighed. All the input waste material was recovered in the form of output streams with a very minor difference of material loss. Of the total input C&D waste material entering the process (by weight), 44 % of the material was recovered in the form of SRF, 6 % in the form of metals, 28 % was separated as fine fraction, 18 % as reject material and 4 % as heavy fraction. C&D waste understandably contained a high mass fraction of building material (i.e. stone/rock, sand, concrete etc.) and the major part of it was sorted out as the fine fraction (28 wt. %) in the screening section after primary shredding. The heavy fraction comprised of unshredded heavy particles of stone/rock, building blocks and some heavy pieces of metal and wood as well. The mass balance of SRF production from C&D waste is shown in Figure 10.

In the SRF production, the energy flow balance from the input waste stream (C&D waste) into the output streams was calculated based on the material flow analysis (MFA) approach (described in Section 2.8.) By using the law of energy conservation, the input energy content of C&D waste was calculated from the sum of the energy content of the output streams. In order to calculate the energy content of the output streams, the heating value (NCV, MJ/kg) of the stream (given in Table 7) was multiplied by the respective total mass of the stream (Figure 10). Energy recovered in the form of SRF was 74 % and 72 % of the total input energy content of C&D waste to the process on wet and dry basis of material respectively. The energy associated with the reject material, fine fraction, heavy fraction and metal streams was due to the mass fraction of combustible components in those streams. The difference between the measured and calculated values of the input energy content is calculated as an error value. The energy flow balance in the process streams of SRF production from C&D waste is shown in Figure 11.

Energy consumed in order to produce SRF from 74 tonnes of C&D waste was calculated (Paper III) in terms of in-plant operations and out-plant operations. In-plant operations comprised of unit operations/sorting techniques, the dust extraction system and material handling machinery (wheel loader and excavator) in the MT waste sorting plant. Out-plant operations included logistical means (vehicles) to collect C&D waste from its collection points and also delivery of output streams (SRF, metals, reject material, fine fraction and heavy fraction) to customers' premises. Energy consumed per unit tonne of feed (input waste stream of C&DW) for in-plant operations and out-plant operations was calculated as 50 kWh and 100 kWh respectively. This showed that the transportational means required to collect and deliver material, requires more energy than the energy required by the process/plant itself to produce SRF.

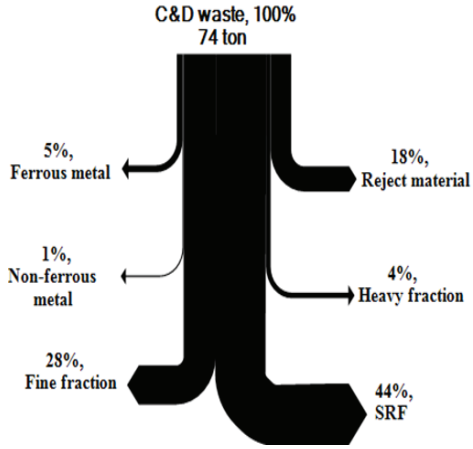


Figure 10: Mass balance of SRF production from construction and demolition waste (wet basis of material) (Paper III)

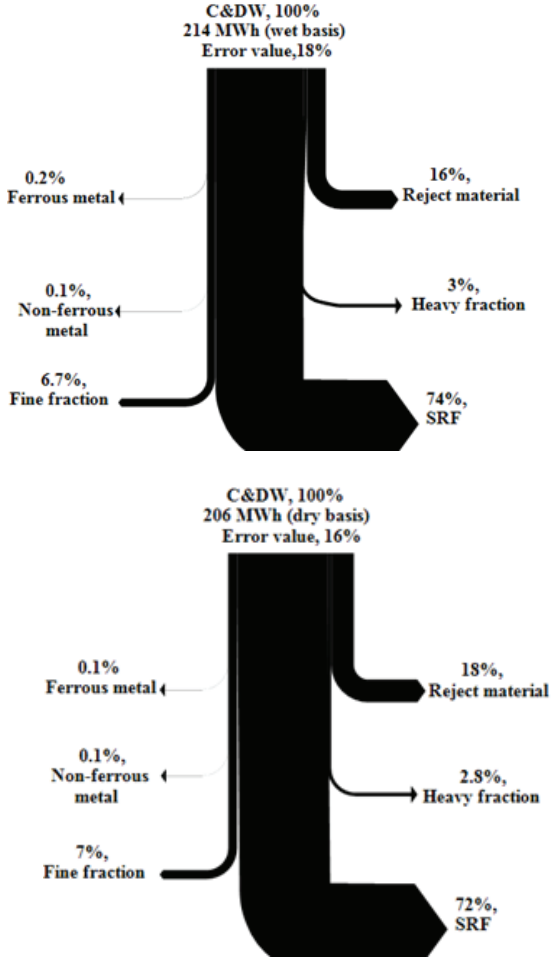


Figure 11: Energy flow balance in process streams of SRF production from construction and demolition waste (Paper III)

In the material balance of SRF production from C&D waste, the mass flow of the input stream's components, i.e. paper & cardboard, plastic (soft), plastic (hard), wood, rubber and foam, into the output streams was determined (Paper III). The mass of the component (on wet basis) in the streams (input and output) was calculated based on the composition of the streams (see Section 4.3) and the mass balance of SRF production (Figure 10). Recovery of plastic (soft) and paper & cardboard in the SRF was higher than the recovery of other waste components. Of the mass of plastic (soft) and paper & cardboard entering the process, 84 % and 82 % respectively were recovered in the SRF. Recovery of wood in the SRF was lower than expected. Of the mass of wood entering the process, 72% was recovered in the SRF. A considerable mass fraction of wood and paper & cardboard was found in the reject material, i.e. 8% and 8.5% respectively of their input mass to the process.

Components of paper & cardboard and wood found in the reject material were mainly those having a larger particle size (> 200 mm), irregular in shape (for example, some paper & cardboard components in rolled form) or heavy in weight/density (some unshredded components in primary shredding). Of the mass of textile and plastic (hard) entering the process, 70% and 68% respectively were recovered in the SRF and 16% and 22% were separated into the reject material. Plastic (hard) found in the reject material mainly consisted of PVC plastics. In the case of rubber material, the major mass fraction of input rubber was found in the reject material, i.e. 58%, and only 22% was recovered in the SRF. As described earlier (in the elemental analysis of waste components, Table 8), rubber, plastic (hard) and textile were measured to contain the highest concentration of polluting elements and PTEs among the waste components and, therefore, significant amounts of these components were sorted/separated out into the reject material by the NIR sorting units in the process.

4.3 Composition of input and output streams (Paper III)

The composition of the input and output streams of SRF production from C&D waste was determined through manual sorting of their respective combined samples (Table 2) into waste components such as paper & cardboard, wood, plastics, metals, textile rubber, foam and inert material. In the composition of C&D waste, mass fraction of wood, building material (i.e. stone/rock/building blocks, sand and concrete etc.) and fines was 23.6 %, 14.2 % and 16.6 %, respectively. The mass fraction of paper & cardboard and plastics (soft and hard) in C&D waste was 12 % and 9.6 %, respectively. In Finland, C&D waste contains more combustible material (especially wood) than in central Europe. The SRF derived from C&D waste was enriched in wood, paper & cardboard and plastics. In the composition of SRF, the mass fraction of wood, paper & cardboard and plastics (soft and hard) was 38.0 %, 22.0 % and 16 %, respectively. The reject material stream mainly comprised building material, rubber and glass. A considerable mass fraction of wood was also found in the reject mate-

rial stream. The composition of input and output streams in SRF production from C&D waste is given and discussed in Paper III.

The energy-based composition of SRF produced from C&D waste was calculated from the composition of SRF (on mass basis) and NCVs of the waste components. In order to calculate the energy-based composition of SRF, the mass fractions of the SRF components were multiplied by their respective net calorific values. The majority of the energy of the SRF was contained by wood, i.e. 37% of the total energy of the SRF. Plastics (soft and hard) and paper & cardboard accounted for 31% and 18% of the total energy content of SRF, respectively. The energy-based composition of SRF produced from C&D waste is shown in Figure 12.

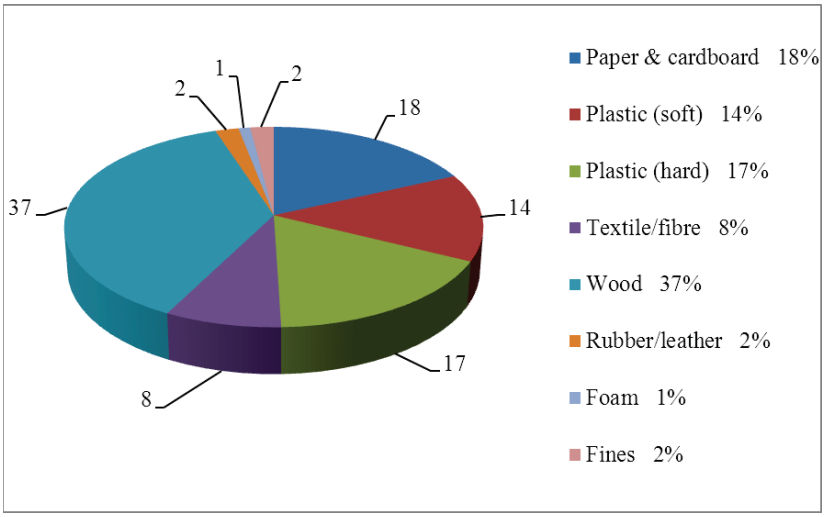


Figure 12: Energy-based composition of SRF produced from construction and demolition waste (Paper III)

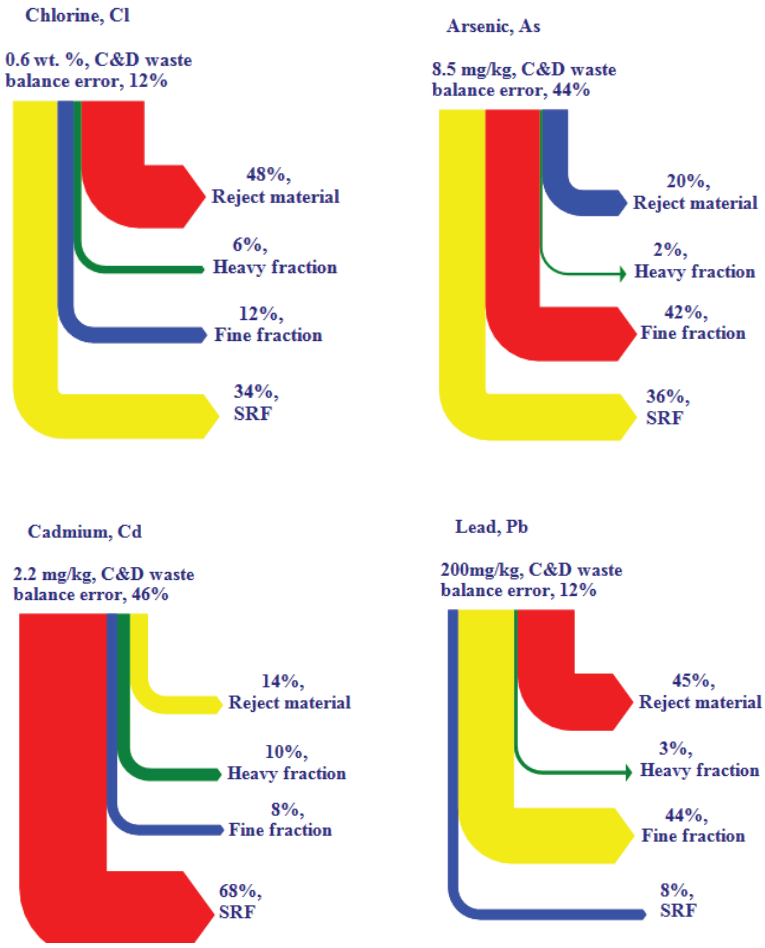
4.4 Elemental balance of SRF production from C&D waste (Paper IV)

In the elemental balance (shown in Figure 13), a higher mass fraction of the input chlorine (Cl) and lead (Pb) was found in the reject material than in other output streams. Of the chlorine and lead content entering the process (by weight), 48 % and 45 % respectively were concentrated in the reject material. In the case of arsenic (As) and mercury (Hg), the fine fraction became the most contaminated of the output streams. Of the input arsenic and mercury content to the process, 42 % and 64 % respectively was found in the fine fraction stream. In contrast, a higher mass fraction of the input cadmium (Cd) entering to the process, was found in the SRF than in the other output streams, i.e. 68 %. The elemental balance of SRF production from C&DW is shown in Figure 13.

The high recovery of paper & cardboard, plastic (soft) and wood from the input waste stream (C&D waste) in the SRF stream effectively reduced the concentration of polluting elements and PTEs in the SRF. On the other hand, the high mass fraction of input rubber, plastic (hard, mainly PVC plastics) and textile (especially synthetic type) was sorted into the reject material and thus waste components, especially those containing a high chlorine content, were routed into the reject material stream. The high mass flow of arsenic (As) and mercury (Hg) into the fine fraction stream was linked with the fact that the majority of components with a high concentration of the said elements were shredded to a smaller particle size (< 15 mm) in primary shredding and screened out in the screening section of the process. In the elemental analysis of waste components (Table 8), textile was measured to have a higher concentration of arsenic (As) than the other waste components. Among the waste components, plastic (soft) and textile were measured to contain a higher mercury (Hg) concentration. In the process, it was noticed that a relatively low moisture content (i.e. 14.0 wt. %) of the input waste stream (C&D waste) affected (positively) the proper sorting of combustible components (especially paper & cardboard, wood and soft plastic) into SRF by air classifier. Sorting of highly chlorinated plastic (PVC plastic) and rubber into the reject material was performed by NIR sorting technology.

The sorting of highly chlorinated waste components into the reject material and the high recovery of combustible components (paper & cardboard, wood and soft plastics) were noticed to be very efficient through the positive sorting of the NIR sorting unit. A lower moisture content (i.e. 14.0 wt. %) of the input stream of C&D waste could have facilitated the better sorting of waste components performed by air classifiers and NIR sorting units in the process, as this was not observed in the case of SRF produced from C&IW with a higher moisture content (25.6 wt. %). However, there was still a noticeable mass fraction of combustibles (especially wood and paper & cardboard) in the reject material (section 4.3), most of these components were larger in particle size (> 200 mm) or irregular in shape (i.e. not properly shredded in primary shredding). Recovery of these combustibles into the SRF stream could have further reduced the concentration of polluting elements and PTEs and enhanced the yield of SRF. The higher mass flow of cadmium (Cd) in the SRF compared with other output streams reflected the fact that waste components containing a high concentration of cadmium found their way through the unit operations (especially the air classifier and NIR sorting unit) into the SRF stream. In the elemental analysis of waste components (Table 8), rubber was measured to contain 5.2 mg/kg of cadmium, which was higher than in other components. It could be that some lightweight components of rubber with a high concentration of cadmium (Cd) were classified by air classifier and put into the SRF stream. The other possibility could be that components containing high levels of cadmium might have been picked by the NIR sorting unit and put into the SRF stream (as due to the black colour of the conveyor belt the NIR sorting unit does not recognize components that are black/dark in colour).

The specific load of polluting elements and PTEs in unsorted C&D waste contributed by various waste components was calculated (Paper IV) based on the composition of C&D waste (Section 4.3) and the elemental analysis of waste components (Table 8). In unsorted C&D waste, plastic (hard), rubber and textile shared the maximum chlorine load, i.e. 40 %, 38 % and 15 %, respectively, of the total chlorine load. Among the waste components, textile carried a far higher load of arsenic (As) in unsorted C&D waste, i.e. 45% of the total arsenic load. The load of cadmium in unsorted C&D waste was mainly carried by rubber, i.e. 58% of the total load. Plastic (hard) was also calculated to carry 20 % of the cadmium load and it was also found to contribute the major load of lead (Pb), i.e. 65 % of the total load of lead in unsorted C&D waste. Textile carried about 20 % of the load of lead (Pb). The specific elemental load contribution by waste components in unsorted C&D waste is presented and discussed in Paper IV.



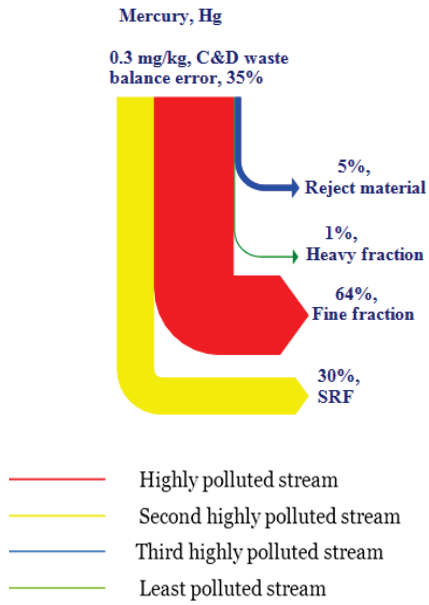


Figure 13: Elemental balance of SRF production from construction and demolition waste (Paper IV)

Major findings

- In an industrial-scale SRF production from construction and demolition waste, of the the total input waste material to the process, 44 wt. % was recovered in the form of SRF and 6 wt. % as metals (ferrous and non-ferrous), 28 wt. % was separated as fine fraction, 18 wt. % as reject material and 4 wt. % as heavy fraction. Energy recovered in the form of SRF was 74% of the feedstock energy content. The energy consumed to process 74 tonnes of C&D waste in the MT plant to produce SRF was calculated in terms of in-plant and out-plant operations. Energy consumed by in-plant and out-plant operations per unit tonne of feedstock was 50 kWh and 100 kWh, respectively.
- C&D waste mainly consisted of wood, building material, paper & cardboard and metals components. In the composition (weight-based) of C&D waste, the mass fraction of wood, paper & cardboard and metals was 23.6%, 12% and 10%, respectively. The composition (weight-based) of SRF derived from C&D was dominated by wood, paper & cardboard and plastics, i.e. 38%, 22% and 16%, respectively. The reject material stream mainly contained inert material (i.e. stone/rock, concrete and building blocks etc.), highly chlorinated rubber and PVC plastic.
- In the elemental balance of SRF production from C&D waste, the majority of the chlorine (Cl), lead (Pb), mercury (Hg) and arsenic (As) (in the feedstock) entering the process was separated/sorted into non-SRF

streams, i.e. reject material, fine fraction and heavy fraction. A higher mass of chlorine (Cl) and lead (Pb) entering the process was found in the reject material as compared with other output streams i.e. 48% and 45% respectively of the input chlorine and lead content entering the process was found in the reject material. The majority of the arsenic (As) and mercury (Hg) content travelled to the fine fraction, i.e. 42% and 64%, respectively. In the case of cadmium, most of it, i.e. 68%, was found in the SRF.

- Among the components of C&D waste, rubber, plastic (hard) and textile (especially synthetic type) were identified as a potential source of polluting elements and PTEs. In contrast, wood, paper & cardboard and plastic (soft) were found to have the lowest content of polluting elements and PTEs.

5 Material and energy balance of SRF production from municipal solid waste

(Papers V and VI)

The material and energy balance of solid recovered fuel (SRF) production from municipal solid waste (MSW) is presented in this chapter. The SRF was produced on industrial scale from a batch of 30 tonnes of MSW in a mechanical treatment (MT) waste sorting plant. The stream of MSW used to produce SRF was energy waste collected from households (Paper V). The energy waste was source-separated at the household level and contained more than 75 wt. % of energy-related waste components: paper & cardboard, plastics, textile, wood, rubber, foam material etc. along with a small wt. % of non-energy-related waste components such as inert material (metals, glass, and stones) and food waste, due to some mis-sorting. The results presented in this chapter include mass, energy, material (Paper V) and elemental (Paper VI) balances of SRF production. The mass flow of polluting elements and PTEs in SRF production is determined (Paper VI) based on the elemental balance of SRF production. In MSW, potential source components for polluting elements and PTEs are identified based on the elemental analysis of waste components (Paper VI). The specific load of various elements in MSW contributed by waste components is determined (Paper VI) based on the composition of MSW (Paper V) and elemental analysis of components (Paper VI). The whole of this work is presented in appended Papers V and VI.

5.1 Proximate & ultimate and elemental analysis of process streams and waste components: SRF produced from MSW (Paper V and Paper VI)

The net calorific value of SRF derived from MSW was measured as 20.2 MJ/kg (a.r. basis). This high calorific value of the SRF was due to the significant contribution of paper & cardboard and plastics. Plastics were reported as major contributors to the high calorific values of the fuel (Rotter et al., 2004). The biomass content as a share of bio carbon measured in the SRF was 50.8%. Paper & cardboard and wood were the major contributors to the biomass content in this SRF. Biogenic components of SRF in the range of 40%–80% were reported in the literature (Hansen et al., 1998). The high ash content in the heavy fraction, fine fraction and reject material streams was due to the high mass fraction of incombustible impurities (especially stone/rock, glass and to some extent metals). The moisture content in the fine fraction stream was higher than in other streams, owing to the biowaste (i.e. food waste) components in it. The laboratory analysis of the streams (input and output) produced in SRF production from MSW (energy waste collected from households) is given in Table 10.

Table 10: Laboratory analysis results of process streams in SRF production from MSW (energy waste collected from households) (mean value of three laboratory test sub-samples) (Paper V)

Streams	Moist cont. wt%	Ash 550°C wt%	Volat. matter wt%	Bio[a] cont. %C	C (d.) wt%	H (d.) wt%	N (d.) wt%	S (d.) wt%	O_{calc} (d.) wt%	NCV (a.r.) MJ/kg	NCV (d.) MJ/kg
MSW[b]	13.5	22.4	n.a.	n.a.	47.0	6.2	0.5	0.2	19.6	16.7	19.6
SRF	15.0	9.8	79.4	50.8	53.0	7.4	0.6	0.2	28.0	20.2	22.4
Reject[c]	26.8	32.5	n.a.	n.a.	40.3	5.2	0.9	0.5	16.3	12.0	16.8
Fine f.[d]	33.0	50.3	n.a.	n.a.	28.0	3.6	0.9	1.0	14.8	7.3	12.0
Heavy f[d]	8.9	96.0	n.a.	n.a.	8.3	1.1	0.2	0.1	4.0	2.5	3.0

[a] Bio. Cont. represents the biomass content (bio carbon)
[b] MSW: Energy waste collected from household
[c] Reject represents the reject material stream
[d] Fine f. and Heavy f represent the fine fraction stream and heavy fraction stream respectively

The source of polluting and PTEs in unsorted MSW was identified (Paper VI) based on the elemental analysis of components of MSW (Table 11). Rubber was identified as a potential source of chlorine (Cl), containing 8.0 wt. % of chlorine. Rubber material also contained components of rubber shoes. The high concentration of chlorine in rubber was in agreement with the previous results obtained from elemental analysis of the components of C&IW and C&D waste. Among waste components, it was recommended to direct shoes away from the SRF stream (Velis et al., 2013) as it was one of the components having a high chlorine content (Velis et al., 2012). Food waste was measured to have 1.2 wt. % of chlorine (Cl). The chlorine concentration in food waste could be due to food containing salt in the food waste components. Among the waste components, textile was measured to contain a higher concentration of bromine (Br). Flame-retardant textiles have been reported (Vainikka et al., 2011; Vainikka and Hupa, 2012; Wua et al., 2014) as a potential source of bromine. A higher concentration of lead (Pb) and cadmium (Cd) was found in plastic (hard) than in other components of MSW. Textile and rubber were measured to contain 0.2 mg/kg of mercury (Hg) each, which was higher than that found in other components. The elemental analysis of the components of MSW (energy waste collected from households) is given in Table 11. Among the output streams, reject material was measured to contain 2.7 wt. % of chlorine (Cl), which was higher than that measured in other output streams (see Table 12). The high chlorine concentration of the reject material was due to the high mass fraction of rubber and plastic (PVC plastic) contained in it. The chlorine (Cl) content of the input waste stream (MSW) was measured as 1.5 wt. %. In the SRF produced from MSW, the chlorine content was reduced to more than half. The bromine (Br) content in the reject stream was measured to be more than in other streams. Most likely, the bromine concentration was due to the textile

component, especially flame-retardant textiles. The fine fraction stream was found to contain 8.0 mg/kg, d. of arsenic (As) and was higher than in other streams. This could be due to waste components containing a high concentration of arsenic (As) and shredded in primary shredding to a small particle size (< 15 mm) and screened out as fines in the screening section. The fine fraction and reject material were measured to contain 180 mg/kg and 160 mg/kg lead (Pb) content, respectively. Among the waste components, plastic (hard) was measured to contain a higher level of lead (Pb), at 500 mg/kg. The mercury (Hg) content in the fine fraction stream was found to be much higher than in the other output streams i.e. 0.8 mg/kg.

Table 11. Elemental analysis of components of MSW (energy waste collected from households) (mean value of three laboratory sub-sample tests, dry basis of material) (Paper VI)

#	Element	Unit	Paper & cardboard	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood	Food waste
1	Cl	wt %, d	0.15	1.6	0.83	1.1	8.0	0.75	0.05	1.2
2	F	wt %, d	0.002	0.003	0.004	0.004	0.001	<0.001	<0.001	0.002
3	Br	wt %, d	0.001	0.001	0.001	0.008	0.001	0.001	0.001	0.001
4	Na	mg/kg, d	1400	570	1300	3700	980	800	220	11200
5	K	mg/kg, d	940	440	1200	1500	420	670	710	7600
6	Mn	mg/kg, d	30	25	40	40	30	25	50	60
7	Cr	mg/kg, d	15	68	40	5300	88	38	7.0	38
8	Cu	mg/kg, d	30	24	37	77	1400	40.0	4.7	140
9	Ni	mg/kg, d	6.0	25	18	30	32	17	3.3	14
10	Zn	mg/kg, d	47	170	160	310	3800	3800	20	110
11	Sb	mg/kg, d	3.0	56	5.0	62	170	2.8	1.8	3.4
12	As	mg/kg, d	0.43	0.61	1.0	2.4	0.6	0.5	0.1	0.8
13	Cd	mg/kg, d	1.2	9.0	0.5	3.1	1.5	0.5	0.12	0.1
14	Co	mg/kg, d	1.0	2.0	1.4	2.4	4.8	1.6	<0.5	1.4
15	Pb	mg/kg, d	12.0	500	20	63.0	370	38.0	3.0	120
16	Mo	mg/kg, d	0.9	1.6	20	4.0	2.2	1.3	0.5	1.8
17	Se	mg/kg, d	0.8	1.2	0.8	1.0	1.0	1.6	<0.53	1.1
18	Tl	mg/kg, d	<0.5	<0.5	<0.5	0.5	0.5	<0.5	<0.5	-
19	V	mg/kg, d	4.1	2.2	6.5	6.2	4.3	5.0	0.1	4.3
20	Hg	mg/kg, d	0.05	0.05	0.1	0.2	0.2	0.1	0.05	0.05

The mercury content in the reject stream was also on the higher side, i.e. 0.5 mg/kg. The elemental analysis of various streams produced in SRF production produced from MSW (energy waste collected from households) is given in Table 12. Among the waste components of MSW, rubber, plastic (hard) and textile (especially the synthetic type) were identified as a potential source of polluting elements and PTEs. In contrast, wood, paper & cardboard, plastic (soft) and foam were identified as containing the lowest amount of polluting and PTEs among the components of MSW.

Table 12. Elemental analysis of input and output streams produced in SRF production from MSW (energy waste collected from households) (mean value of three laboratory sub-sample tests, dry basis of material) (Paper VI)

#	Element	Unit	Input waste (MSW)	Reject material	Fine fraction	Heavy fraction	SRF
1	Cl	wt %, d	1.5	2.7	1.1	0.04	0.6
2	F	wt %, d	0.01	0.05	0.0001	0.002	0.01
3	Br	wt %, d	0.002	0.01	0.0001	0.001	0.004
4	S	wt %, d	0.2	0.5	1.0	0.1	0.2
5	Na	mg/kg, d	7920	9190	18880	7110	1590
6	K	mg/kg, d	3530	4475	8500	13870	920
7	Ca	mg/kg, d	30625	36600	56260	82350	28925
8	Mg	mg/kg, d	2960	3140	6420	4560	1390
9	P	mg/kg, d	380	980	1230	310	340
10	Al	mg/kg, d	12400	15990	23320	48110	6260
11	Si	mg/kg, d	41500	40410	54750	32490	9240
12	Fe	mg/kg, d	6680	3760	11610	8340	1390
13	Ti	mg/kg, d	2480	2570	2740	4390	1990
14	Cr	mg/kg, d	150	450	210	80	370
15	Cu	mg/kg, d	1240	3865	690	710	270
16	Mn	mg/kg, d	105	415	235	175	55
17	Ni	mg/kg, d	50	250	105	30	11
18	Zn	mg/kg, d	560	1380	735	50	230
19	Sb	mg/kg, d	70	140	80	2.2	540
20	As	mg/kg, d	3.4	4.0	8.0	4.4	0.7
21	Ba	mg/kg, d	468	490	1510	360	280
22	Cd	mg/kg, d	1.0	1.0	2.2	0.2	0.7
23	Co	mg/kg, d	3.6	6.0	8.5	4.4	3.4
24	Pb	mg/kg, d	280	160	180	25	30
25	Mo	mg/kg, d	12.4	8.0	20	1.8	3.2
26	Se	mg/kg, d	1.2	1.4	2.2	3.8	0.5
27	Tl	mg/kg, d	0.5	0.5	0.5	0.4	0.5
28	Sn	mg/kg, d	26	68	40	8.0	12
29	V	mg/kg, d	20	11.0	25.0	54	8.0
30	Hg	mg/kg, d	0.15	0.5	0.8	0.1	0.1

5.2 Mass, energy and material balances of SRF production from MSW (Paper V)

The mass balance of the SRF production was established for a batch of 30 tonnes of MSW fed to the MT waste sorting plant. All the output streams produced from input waste were weighed. The input waste material was recovered in the form of output streams with a negligible mass difference. In the process, of the total input MSW (by weight), 72 % of the material was recovered in the form of SRF, 3 % in the form of metals, 11 % was separated as reject material, 12 % as fine fraction and 2 % as heavy fraction. The mass balance of the SRF production from MSW is shown in Figure 14.

The energy flow balance in the process streams of SRF production was determined based on the law of energy conservation and was calculated using the MFA approach (described in section 2.8). The energy balance of the input waste stream was calculated from the sum of the energy content of the output streams. The energy content of the output streams was calculated by multiplying their NCV (MJ/kg, dry and as-received basis, given in Table 10) by their respective mass (Figure 14 and moisture content of streams given in Table 10 aswell). The difference between the measured and calculated energy value of the input energy stream (MSW) is given as an error value. Very high levels of energy were recovered from the input energy content of MSW, i.e. 86 %, in the form of SRF. The energy flow balance in process streams of SRF production from MSW is shown in Figure 15. The energy consumed in processing the batch of 30 tonnes of MSW in the MT plant to produce SRF was calculated in terms of in-plant operations and out-plant operations. In-plant operations included the unit operations/sorting techniques (described in Section 2.2), dust extraction system and material handling machinery (wheel loader and excavator) used in the MT plant. Out-plant operations included the logistical means (i.e. vehicle/trucks/lorries) used to collect MSW from its collection points and deliver it to the processing plant location, it also included the transportation delivery of the output streams (i.e. SRF and others) to the customers' premises. The energy consumed per unit tonne of feed for in-plant operations and out-plant operations was calculated as 70 kWh and 242 kWh respectively (Paper V).

In the material balance of SRF production from MSW, a very high mass fraction of paper & cardboard, wood and plastic (soft) was recovered in the SRF, i.e. 88 %, 90 % and 85 %, respectively. The recovery of textile in the SRF was also on the high side, i.e. 82 % of its input mass. Of the input plastic (hard) and rubber, 14 % and 55 % respectively was found in the reject material. The plastic (hard) found in the reject material was mainly PVC plastic components and the rubber was highly chlorinated. These were routed away by the NIR sorting units from the input waste stream into the reject material. The material balance of SRF production from MSW (energy waste collected from households) is presented and discussed in Paper V.

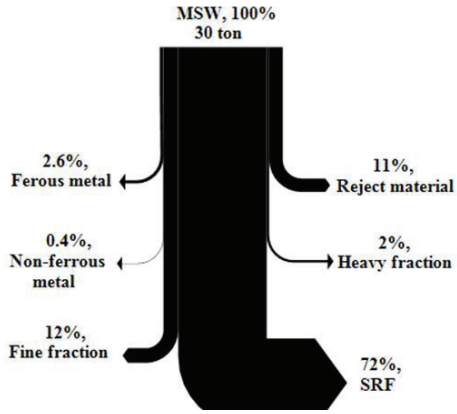


Figure 14. Mass balance of SRF production from MSW (energy waste collected from household) (wet basis) (Paper V)

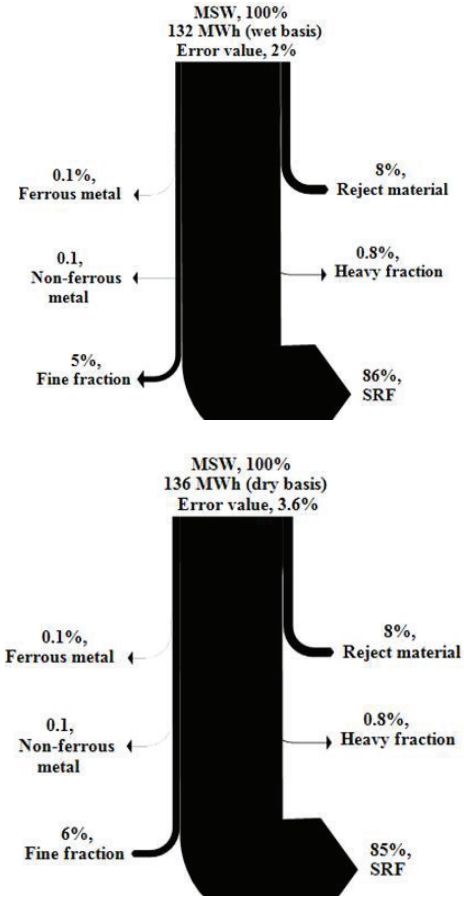


Figure 15: Energy flow balance in process streams of SRF production from MSW (energy waste collected from household) (Paper V)

5.3 Composition of input and output streams

In the composition (on weight basis) of MSW, plastics and paper & cardboard were the dominant components at 28.6 % and 24.5 %, respectively. The SRF produced from MSW was highly enriched with plastics and paper & cardboard. In the SRF, the mass fraction of plastic (soft and hard) and paper & cardboard was 32.6 % and 30 %, respectively. The mass fraction of textile in the SRF was 10.0 %. The reject material stream mainly comprised rubber, plastic (hard), textile and biowaste (especially food waste). As described earlier, most of the rubber and plastic (hard) components found in the reject material were highly chlorinated and PVC plastics. Textile components separated in the reject material were mainly synthetic type (containing a relatively high chlorine and bromine content), larger in particle size (< 200 mm) or in rolled form (non-shredded rolls). The fine fraction stream was found mainly to contain glass, biowaste (food waste) and stones i.e. 22.2 %, 20 % and 16.8 %, respectively. The biowaste found in the fine fraction stream was shredded in primary shredding (< 15 mm) and screened out in the screening section of the process. The composition of the input and output streams of SRF production from MSW is given and discussed in Paper V.

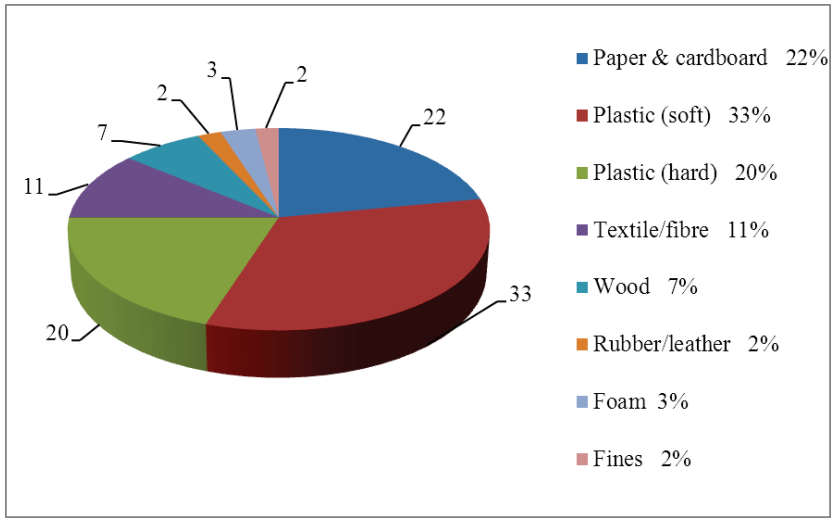


Figure 16: Energy-based composition of SRF produced from MSW (energy waste collected from household) (Paper V)

The energy-based composition of the SRF produced from MSW was calculated from its composition on a mass basis and the net calorific values of the waste components. The energy content of the SRF was dominated by plastic (soft), paper & cardboard and plastic (hard) i.e. 33 %, 22 % and 20 %, respectively. Textile carried 11 % of the energy content of the SRF. The energy-based composition of the SRF produced from MSW is shown in Figure 16.

5.4 Elemental balance of SRF production from MSW (Paper VI)

In the SRF production, a higher mass fraction of the input chlorine (Cl) and cadmium (Cd) content to the process was found in the SRF than in other output streams i.e. 55 %, 62 %, respectively. While a higher mass fraction of input arsenic (As) and mercury (Hg) content to the process was found in the fine fraction stream i.e. 45 % each. Lead (Pb) was found comparatively homogeneously distributed among the SRF, fine fraction and reject material streams i.e. 38 %, 32 % and 28 %, respectively, of the lead (Pb) content entering the process. The elemental balance of SRF production from MSW (energy waste collected from households) is shown in Figure 17. The difference in the measured and calculated values of the input element concentration is calculated as a balance error.

In the SRF production, the components of the input waste stream were sorted into the various output streams based on material properties such as particle size, density/weight, magnetic properties, and infrared (IR)/spectral properties. Based on the results of the composition of the process streams (see Section 5.3), the elemental analysis of the components of the input waste stream (Table 11) and the elemental balance of SRF production process (Figure 17), certain factors were identified which caused the higher mass flow of chlorine and cadmium in the SRF stream as described below.

In the elemental analysis of the waste components, rubber, plastic (hard) and textile (synthetic) were identified as potential sources of chlorine (Cl). Plastic (hard) waste components were also measured to have a higher cadmium (Cd) content than the other waste components (see Table 11). In the SRF production, to a certain extent, waste components with a high chlorine and cadmium content were not separated and prevented from entering the SRF stream. Even though a high mass fraction of rubber and PVC plastic was separated into the reject material there were still certain lightweight waste components (of rubber, plastic or textile having a high chlorine and cadmium content) separated into the SRF stream by the air classifier.

On the other hand, the NIR sorting unit could have picked out certain waste components (with a high chlorine and cadmium content) and put them into the SRF stream. One observation related to this issue might be the lack of capacity or proper/regular maintenance checks of the NIR sorting unit (especially the air nozzles). It could also be related to the non-steady flow rate of waste material (sometimes there could be sudden peaks of material flow from the sorting units due to the uneven material feeding at the start of the process) passing through the NIR sorting unit on the conveyor belt. Increasingly, NIR sorting technology capable of removing highly chlorinated plastic polymers is being adopted in newly built SRF production plants (Roos and Peters 2007; Schirmer et al., 2007) but improvements in this sorting technology are necessary for full operational scale (Pieber et al., 2012).

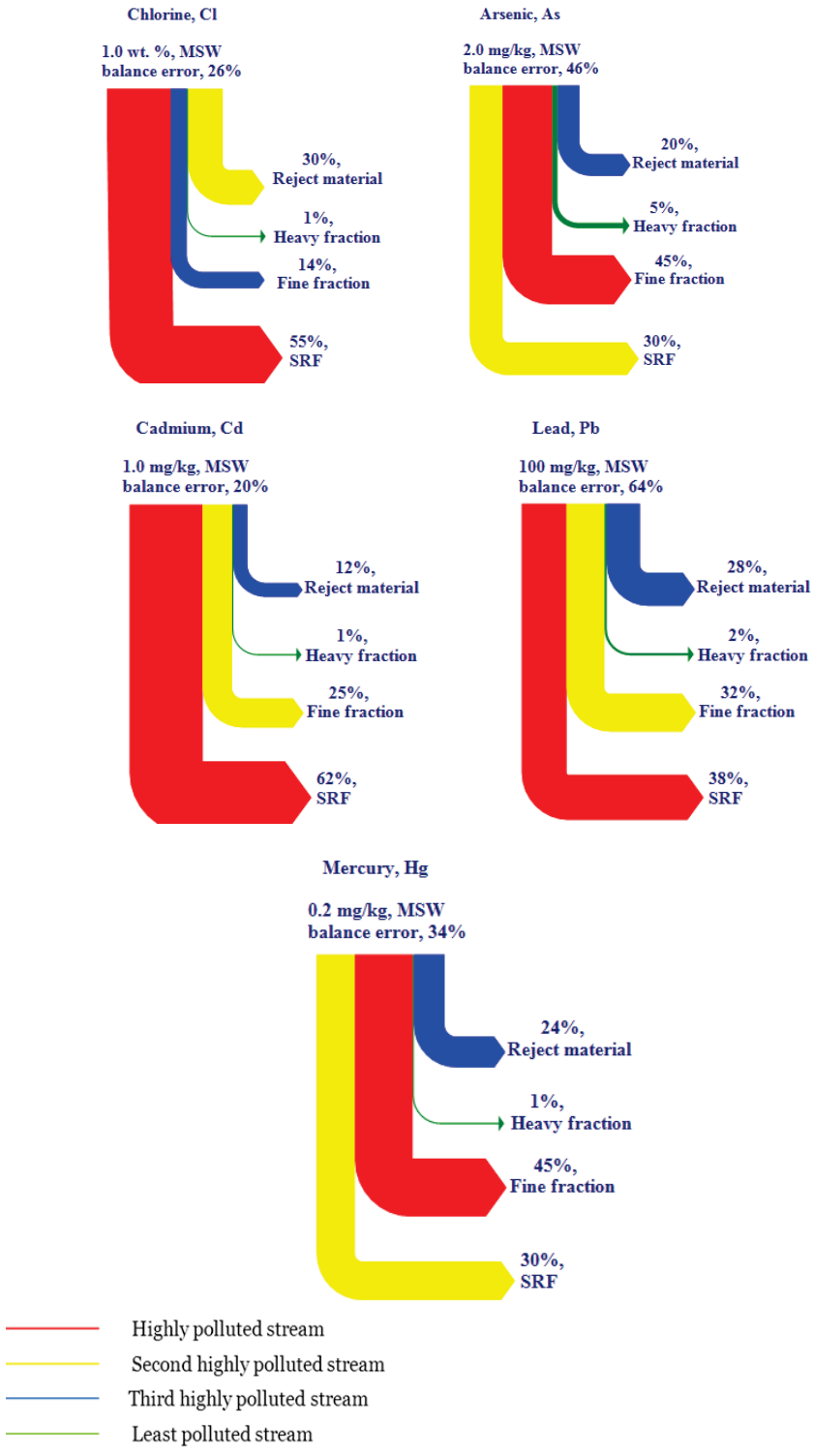


Figure 17: Elemental balance of SRF production from MSW (energy waste collected from household) (Paper VI)

In the case of mercury and arsenic, a higher mass flow of their respective input content was found in the fine fraction stream. This might be linked with the fact that waste components in the input waste stream containing mercury and arsenic were shredded to a smaller particle size (<15 mm) in the primary shredding unit and screened out as fine fraction.

The specific load of polluting elements and PTEs contributed by the various waste components in unsorted MSW was calculated (Paper VI) based on the composition of MSW (section 5.3) and the elemental analysis of the waste components (Table 11). Rubber material carried the maximum chlorine load, i.e. 40 %, of the total chlorine load in unsorted MSW. Plastic (hard) was found to carry 20% of the chlorine load in MSW. Among the waste component, textile and plastic (soft) shared about a 60% load of arsenic (As) in unsorted MSW, i.e. 35% and 25%, respectively, of the total arsenic load. The load of cadmium (Cd) in unsorted MSW was mainly contributed by plastic (hard), i.e. 58% of the total load. Plastic (hard) was also found to carry the major load of lead (Pb), i.e. 62 % of the total load of lead in MSW. Textile, plastic (soft) and rubber were among the prominent contributors of the mercury (Hg) load, i.e. 26%, 24% and 12%, respectively, of the total mercury load in unsorted MSW. The specific elemental load contribution by waste components in unsorted MSW is presented and discussed in Paper VI.

Major findings

- Solid recovered fuel was produced from municipal solid waste (energy waste collected from households) in an industrial-scale mechanical treatment (MT) waste sorting plant. In this process, a significantly large amount of material was recovered in the form of SRF. Of the MSW input to the process, 72 wt. % was recovered as SRF, 3 wt. % as metals (ferrous/non-ferrous) for recycling and the rest was separated as fine fraction, reject material and heavy fraction. Of the energy content input to the process in the form of MSW, 86 % was recovered in the form of SRF. The energy consumed per unit tonne of feedstock was calculated as 70 kWh and 242 kWh by in-plant operations and out-plant operations, respectively.
- In the composition of MSW (energy waste collected from households), plastics and paper & cardboard shared the major fraction of it, i.e. 28.6 wt. % and 24.5 wt. %, respectively. The composition of SRF produced from MSW was further enriched with plastic and paper & cardboard, i.e. 32.6 wt. % and 30.0 wt. %, respectively. The major waste components in the reject material stream were rubber, plastic (hard, PVC plastic) and inert material (glass, stone and fines).
- In the elemental balance of SRF production, among the output streams, higher mass flow of the input chlorine (Cl) and cadmium (Cd) content was found in the SRF, i.e. 55 %, 62 %, respectively. Of the input

concentration of arsenic (As) and mercury (Hg), the highest mass flow was found in the fine fraction, i.e. 45 % each. Lead (Pb) was found comparatively evenly distributed among the SRF, fine fraction and reject material, i.e. 38 %, 32 % and 28 %, respectively, of the lead (Pb) content entering the process.

- In the elemental analysis of components of MSW, rubber, plastic (hard) and textile (especially synthetic type) were identified as a potential source of polluting and PTEs. Conversely, paper & cardboard, wood and plastic (soft) were found to have the lowest content of polluting elements and PTEs.

6 Comparison of major results of SRF production from C&IW, C&DW and MSW

(Paper I – VI)

In this chapter, the major results of the SRF production from three different types of waste material: C&IW, C&DW and MSW, are compared and discussed. The results include the quality and material & energy yield of SRF, the source of polluting and potentially toxic elements (PTEs) in different waste streams, the energy consumed to produce SRF, the energy yield and mass flow of polluting and PTEs in the SRF production.

6.1 Qualitative classification of SRF

Classification of the SRF produced from three different types of waste material was made as per CEN standards (EN 15359) for SRF based on the limit values of three important fuel properties (given in Table 1): net calorific value (NCV, a.r.), chlorine content (%, dry) and mercury content (mg/MJ, a.r.). The classification of the SRF produced from various waste materials is given in Table 13.

Table 13. Classification of SRF produced from different types of waste material

SRF produced from	NCV MJ/kg, a.r.		Chlorine (Cl) wt. %, d		Mercury (Hg) mg/MJ, a.r.	
C&IW	18.0	Class 3	0.62	Class 3	0.004	Class 1
C&DW	18.0	Class 3	0.44	Class 2	0.009	Class 1
MSW[a]	20.2	Class 2	0.58	Class 2	0.004	Class 1

[a] MSW: Energy waste collected from households

The net calorific value of the SRF produced from C&IW, C&DW and MSW (energy waste collected from households) was mainly due to plastics contribution in it. There was a greater plastic mass fraction in the SRF produced from MSW than in with that produced from C&IW and C&D waste. Among the waste components, wood was measured to contain the lowest chlorine (Cl) content. In the case of SRF produced from C&D waste, the high mass fraction of wood effectively reduced the chlorine (Cl) content to 0.4 wt. %, d. The mass fraction of plastics in SRF produced from C&DW was lower than in SRF produced from C&IW and MSW.

6.2 Comparison of product yield

A higher yield of material and energy was obtained from SRF produced from MSW than that produced from C&IW and C&D waste. A comparatively lower moisture content and better particle size distribution (in terms of particle size

and shape) and fewer impurities (i.e. rubber, PVC plastics and metals etc.) in the incoming MSW as compared with C&IW and C&DW were among the main reasons observed, which facilitated the higher yield of SRF. The material and energy yield of SRF production from C&IW, C&DW and MSW are given in Table 14.

Table 14. Material and energy yield of SRF production from C&IW, C&DW and MSW

SRF produced from	Material yield as SRF wt. %	Energy yield as SRF MWh, %
C&IW	62	75
C&DW	44	74
MSW[a]	72	86

[a] MSW: Energy waste collected from households

As discussed earlier, in SRF production from C&IW and C&DW, a significant mass fraction of combustibles (paper & cardboard and wood) was found in the reject material stream, reducing the yield of material and energy in the form of SRF. Combustibles (paper and cardboard and wood) found in the reject stream mainly consisted of waste components with a large particle size (> 200 mm), highly moist (> 25 wt. %) or irregular in shape (in bundle or unshredded form). The recovery of the said components from the reject material into the SRF stream could have effectively enhanced the material and energy yield of the SRF.

6.3 Energy consumed to produce SRF and power available from SRF

The energy consumed to produce SRF from C&IW, C&DW and MSW was calculated (Paper I, Paper III, Paper V) in terms of in-plant operations and out-plant operations (see Section 3.2, 4.2 and 5.2). The power available from the SRF produced from the said three types of waste material was calculated by using a power production efficiency of 31 % of a Finnish combined heat and power (CHP) gasification plant. The result of the energy consumption to produce SRF and power available from the SRF is shown in Figure 18 in the form of a comparison for SRF produced from C&IW, C&DW and MSW (energy waste collected from households).

In each case the energy consumed by out-plant operations was higher than consumed by the in-plant operations. Energy consumed in out-plant operations for MSW was higher than that consumed for C&IW and C&D waste. This was due to the requirement for more logistical means to collect waste from households from various waste collecting points.

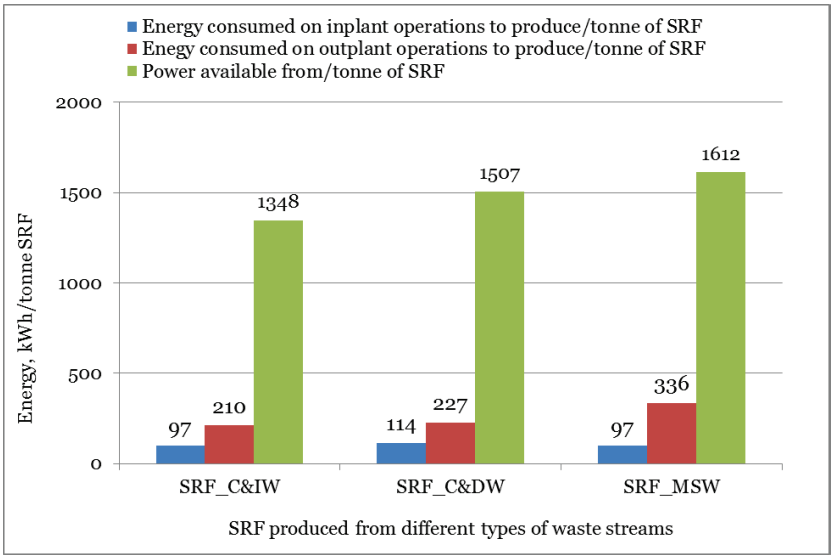


Figure 18. Energy consumed in processing C&IW, C&DW and MSW[a] to produce SRF and the power available from the produced SRF

[a] MSW: Energy waste collected from households

6.4 Identification of source of polluting elements and potentially toxic elements (PTEs) in waste components

The identification of the source of polluting elements and PTEs in various types of waste material (i.e. C&IW, C&DW and MSW) was based on the elemental analysis (see Table 5, Table 8 and Table 11) of their components and the specific elemental load contribution of the components in the waste materials (see Section 3.4, 4.4 5.4). Among the waste components of C&IW, C&DW and MSW, rubber, plastic (hard, especially PVC plastics) and textile (especially synthetic type and flame-retardant textile components) were identified as potential sources of polluting elements and PTEs. The polluting elements and PTEs included chlorine (Cl), lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As).

In the SRF production, the distribution of rubber, plastic (hard, especially PVC plastics) and textile (especially synthetic type and flame-retardant textile components) from the input waste stream into the output streams needs to be monitored carefully as it played a decisive role in defining the elemental quality of SRF. On the other hand, paper & cardboard, wood and plastic (soft) were identified as containing the least amount of polluting elements and PTEs among the waste components.

Based on the elemental analysis of waste components and their specific elemental load contribution, the distribution/separation of rubber, plastic (hard, especially PVC plastics) and textile (especially synthetic type and flame-retardant textile components) from the input waste stream into the output

streams was found to be the most critical in defining the elemental quality of SRF. In this context, the said components are recommended to be directed away from the SRF stream, whereas the maximum recovery of paper & cardboard, wood and plastic (soft) is desired in order to enhance the quality and yield of SRF.

6.5 Mass flow of polluting elements and PTEs in SRF production from C&IW, C&DW and MSW

In this research work, it was observed that the quality and yield of SRF was affected by the type of input waste stream (i.e. C&IW, C&DW and MSW). In SRF production, the characteristics of the input waste stream in terms of composition, moisture content, particle size and shape of waste components was found to have a significant effect on the sorting of waste components in the relevant output stream. The mass flow of polluting elements and PTEs from the input waste stream into the output streams was found to have a direct link with the type and share of waste components distributed in the output streams.

A higher mass flow of polluting elements and PTEs was found in the SRF produced from C&IW in comparison with the SRFs produced from C&D waste and MSW. C&IW processing was found to be complicated because of its high moisture content, and waste components of irregular shape (rolled form of paper and cardboard and textiles) that were large in particle size even after primary shredding. The proper sorting of waste components into the output streams was found to be affected negatively by the said physical properties of the C&IW components. It was noticed that especially the air classifier and NIR sorting units might not perform the sorting of problematic components as designed. A significant mass fraction of combustibles (especially paper and cardboard and wood) was found in the reject material stream that was supposed to be in the SRF stream. In the case of SRF produced from C&D waste, it was found to be less contaminated in terms of polluting elements and PTEs than the SRFs produced from C&IW and MSW. In the case of SRF produced from C&D waste, a high mass fraction of wood in the SRF stream effectively reduced the content of polluting elements (especially chlorine).

6.6 Improving the sorting efficiency of the mechanical processing of waste material

In SRF production from different types of waste materials, based on the results, observations and their comparison, the sorting efficiency of the mechanical processing of waste material can be improved by the following key process-related actions:

- The lightweight components which contained a higher concentration of polluting elements and PTEs (especially chlorine and cadmium) could have been classified by an air classifier (due to their light weight/density) and put into the SRF stream. This issue could be addressed by passing air-classified components through the NIR sorting unit before putting them into the SRF stream. The NIR check could route undesired components away (with negative sorting i.e. sorting the undesired waste components) from the SRF stream.
- Another very important process factor observed which could affect the sorting efficiency of unit operations (especially the air classifier and NIR sorting unit) was balancing the mass flows of the plant through steady feeding of input waste (not trying to feed as much as possible) and adjusting the processes so that the mass flows divided between the processes/unit operations are in line with the designed capacities of the machinery. In other words, too much or sudden peaks of material coming to any of the sorting processes might affect the sorting efficiency of the unit operations. Regular and proper maintenance of plant processes/unit operation equipment (e.g. keeping the air nozzles of the NIR units clean) is also vital to ensure that the machines are working properly and the set-ups are inline.
- Proper/better shredding of input waste stream components in the primary shredder is very helpful in facilitating the unit operations (especially the air classifier and NIR) for better sorting of waste components into the relevant output streams. For example, a considerable mass fraction of combustibles (paper & cardboard and wood etc.) was found in the reject material and heavy fraction streams. The majority of these components had a large particle size (<200 mm, especially wood and textile components) or were heavy in weight/density (paper & cardboard, textile and plastic in bundled/roled form), and were supposed to be in the SRF stream rather than in the reject material.

6.7 Areas of further Advancements in the research

Further innovations and advancements regarding element based waste sorting techniques are needed in SRF production technology to separate the waste components containing undesirable elements; this would be a step forward in transforming the SRF into a mainstream fuel. These techniques could be useful in defining the limit of certain elements' concentration and separating those waste components away from the SRF which contain the polluting and potentially toxic elements beyond the set/desired limit.

Further/advanced automation in the shredding techniques can also be vital in order to optimize the particle size distribution (in terms of particles lengthe and shape) of the waste components. In this context, smart shredder which can sense, for instance the length/diameter of waste components if it is larger than the required one and keeps it within shredding process until it is shredded to desired size in terms of length/diamerete and shape. In the shredding the particle size of the combustible/suiable waste components should not be larger than the desired one so that it gets an appropriate treatment in the separation techniques especially in air classifer and near-infra red (NIR) and get sorted into the relevant output stream. On the other hand, the particle size of the combustible/suitable waste components should be avoided to be in the fines (<15mm) so that these components don't end up in the fine fraction.

Conclusions

In this research work, solid recovered fuel (SRF) was produced from three different types of waste materials through mechanical treatment on industrial scale. The SRF was produced from commercial and industrial waste (C&IW), construction and demolition waste (C&D waste) and municipal solid waste (MSW i.e. energy waste collected from households). The input and output streams produced in SRF production were sampled and treated according to CEN standard methods for SRF. The proximate & ultimate and detailed elemental analysis of the process streams and waste components produced in SRF production were performed. The quality of SRF production was determined through detailed material and energy balances of the SRF production processes. The mass flow of polluting and potentially toxic elements (PTEs) from input to output streams was examined in terms of the elemental balance of SRF production processes. The source of polluting elements and PTEs in the waste materials was identified based on the elemental analysis of the waste components.

In the case of SRF produced from MSW, a higher yield in terms of material and energy recovery was obtained in the form of SRF as compared with SRF produced from C&IW and C&DW. Of the MSW entering the process, 72% was recovered as SRF, equivalent to 86% energy of the input energy content of MSW. Material recovered in the form of SRF from C&IW was 62%, equivalent to 75% of the input energy content of C&IW. Of the C&D waste entering the process, 44% of the material was recovered in the form of SRF, equivalent to 74% of the input energy content of C&D waste. In the SRF produced from MSW, the recovery of paper and cardboard and wood was higher than that recovered in the SRF produced from C&IW and C&D waste. The energy consumed to process waste material to produce SRF was calculated in terms of in-plant and out-plant operations for the three processes separately. The in-plant operations consisted of the unit operations used in the MT plant to sort out the input waste material into the various output streams. The out-plant operations included the logistical means (vehicles/lorries/trucks) to collect waste material from collection points and deliver process products to the customers' premises. For SRF produced from C&IW, C&DW and MSW, the energy consumed in the out-plant operations was 130 kWh, 100 kWh and 242 kWh, respectively, whereas energy consumed in in-plant operations was 60 kWh, 50 kWh and 70 kWh, respectively.

In the case of SRF produced from C&IW, it was found to be comparatively more contaminated with chlorine (Cl), lead (Pb) and mercury (Hg) than the SRFs produced from MSW and C&D waste. In the SRF produced from C&IW, of the input content of chlorine, lead and mercury to the process, 60 %, 58% and 45 % respectively was found in the SRF stream. For SRF produced from C&D waste, the SRF was found to be the least contaminated with chlorine (Cl), lead (Pb) and mercury (Hg) as compared with those produced from C&IW and MSW. In the SRF produced from C&D waste, of the input content of chlorine,

lead and mercury to the process, 34 %, 8 % and 30 % respectively was found in the SRF.

In the SRF production, the quality of the SRF was found to be directly linked with the mass and type of waste components distributed/sorted into the output streams. The sorting of waste components in the output streams was found to be significantly affected by their physical properties, i.e. moisture content, particle size and particle shape. For SRF produced from C&IW and C&D waste, a significant mass fraction of combustible components, i.e. paper and cardboard and wood, were found in the reject material stream which was rather supposed to be in the SRF stream. The major fraction of these combustibles had a large particle size (> 200 mm), were highly moist (>25 wt. %) or irregular in shape (some paper and cardboard and textile components in rolled form etc.). The said physical properties of the waste components were attributed to the type of waste material. In MSW, the components were found to possess better physical properties especially in terms of particle size distribution (i.e. not too many components with a large particle size as there were in the C&IW and C&D waste), particle shape (i.e. components of paper and cardboard and textile were not in rolled form etc.) and moisture content (moisture content of MSW was 13.5 wt. %). In SRF production, the performance of air classifiers and near-infrared (NIR) sorting units play a decisive role in defining the quality and yield of SRF.

Among the waste components, rubber, plastic (hard) and textile (synthetic type) were identified as the potential sources of polluting elements and PTEs. In particular, rubber (black/grey in colour) was consistently found to have a higher chlorine content than other waste components. Rubber in C&IW, C&D waste and MSW was measured to contain 8.0 wt. %, 7.6 wt. % and 8.0 wt. % respectively of chlorine. In order to reduce the concentration of polluting and PTEs effectively in SRF, it is recommended to route rubber (especially black/grey in colour), hard plastics (especially PVC plastics) and textile (synthetic type) away from the SRF. On the other hand, paper & cardboard, wood and plastic (soft) were identified as containing the least polluting elements and PTEs and should be recovered in the SRF to effectively reduce the concentration of polluting and PTEs and enhance the yield of SRF.

The SRF produced from various types of waste materials was found to be qualitatively up to the mark as per standards in terms of economic (net calorific value), technical (chlorine content) and environmental (mercury content) parameters. The quality of SRF was found to be within the range of class 1 – class 3, as per CEN standards for SRF. The extent of variation was relatively higher for the concertation of chlorine, lead and cadmium in the SRF as compared to that of arsenic and mercury. The extent of variation in the said parameters could be a cause of concern for the user of SRF as a mainstream fuel, especially in power production plants. The production of SRF from waste material (especially which is complicated/not feasible to recycle) is a very good and competitive option for waste management, as it recovers value in terms of energy and recyclables from waste and leaves a comparatively very small fraction of waste material to be landfilled.

References

Arena, U., Di Gregorio, F. (2014a). A waste management planning based on substance flow analysis, *Resources, Conservation and Recycling,* 85 (4), 54–66.

Arena, U., Di Gregorio, F. (2014b). Gasification of a solid recovered fuel in a pilot scale fluidized bed reactor. *Fuel* 117 (3) 528–536.

Brunner, P.H., Rechberger, H. (2014). Waste to energy—key element for sustainable waste management, *Waste Management*, 37 (3), 3–12.

Bosmans, A., Vanderreydt, I., Geysenc, D., Helsen, L. (2013). The crucial role of waste-to-energy technologies in enhanced landfill mining: a technology review, *Journal of Cleaner Production,* 55 (9), 10–23.

Brunner, P.H. (2010). Clean cycles and safe final sinks. *Waste Manage. Res.* 28 (7), 575 – 576.

Brunner, P., Rechberger, H. (2004). Practical handbook of material flow analysis. Boca Raton (FL): CRC Press LLC.

Biffaward programme on sustainable use. (2003). Thermal Methods of Municipal Waste Treatment.
<http://www.massbalance.org/downloads/projectfiles/1826-00237.pdf>
[accessed in 2014].

Commission of the European Communities (2005). Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and The Committee of the Regions – Taking sustainable use of resources forward – A Thematic Strategy on the prevention and recycling of waste. Report no. COM (2005) 666 final. European Union.
http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52005DC0666:EN:NOT

Carone, M. (2008). Refuse-derived fuel projects in China under a legal perspective. *China Law Practice, 22 (6), 26–28.*

Choi, Y.-S., Han, S., Choi, H.-S., Kim, S.-J. (2012). Characterization of Korean solid recovered fuels (SRFs): An analysis and comparison of SRFs. *Waste Manage. Res.*, 30 (4), 442–449.

Caspary, G., Evans, M., Buxtorf, L. (2007). Stabilising energy-related greenhouse gas emissions: making "technology wedges" feasible. *Renewable Energy,* 32 (5), 713–726.

Dunnu, G., Maier, J., Scheffknecht, G. (2010a). Ash fusibility and compositional data of solid recovered fuels. *Fuel,* 89 (7), 1534–1540.

Dunnu, G., Maier, J., Scheffknecht, G. (2010b). Drag coefficient of solid recovered fuels (SRF). *Fuel,* 89 (12), 4053–4057.

European Commission, (2008). Directive on Waste and Repealing Certain Directives. Official Journal, L312, 22.11.2008, 3–28 Brussels, Belgium. Available at: <http://eurlex.europa.eu/LexUriServ/ [accessed in 2015].

Eurostat (2013). *Greenhouse gas emissions by sector*. Available at: http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdcc2 10. 331/2013 (2013). Valtioneuvoston asetus kaatopaikoista [Government decree on landfills]. (In Finnish.) [accessed in 2015].

Eurostat. Municipal waste. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/sectors/municipal waste. [accessed in 2015].

European Integrated Pollution Prevention and Control Bureau (IPPC Bureau) (2006). Reference Document on Best Available Techniques for Waste Incineration. Available at: http://eippcb.jrc.es/reference: European Commission.

Eurostat (2009). Total gross electricity generation. Available at: http://epp.eurostat.ec.europa.eu/tgm/table.do;jsessionid=9ea7971b30dfa94cac95eba040bda1c3cf475226a049.e34RaNaLaN0Mc40LcheTaxiLbxmNe0?tab=table&plugin=1&language=en & pcode=ten00087.

EN 15359 Solid Recovered Fuels – Specifications and Classifications. Available at: <http://www.din.de/cmd;jsessionid=DU4UESZJIM2HDAO3COIITR7H.2?languageid=en&workflowname=dinSearch> [accessed in 2014].

EN 15442 Solid recovered fuels – methods for sampling. Available at: <http://www.din.de/cmd;jsessionid=DU4UESZJIM2HDAO3COIITR7H.2?languageid=en&workflow name=dinSearch> [accessed in 2014].

EN 15443. Solid recovered fuels – methods for the preparation of the laboratory sample. Available at: <http://www.din.de/cmd;jsessionid=DU4UESZJIM2HDAO3COIITR7H.2?languageid=en&workflowname=dinSearch> [accessed in 2014].

ERFO - Facts and figures about SRF. http://erfo.info/Facts-and-figures.15.0.html [accessed in 2014].

Gawlika, B., Sobieckaa, E., Vaccaroa, S., Cicerib, G. (2007). Quality management organization, validation of standards, developments and inquiries for solid recovered fuels—an overview on the QUOVADIS-project. *Energy Policy* 35 (12) 6293–6298.

Gohlke, O., Martin J. (2007). Drivers for innovation in waste-to-energy technology. *Waste Management Research.* 25 (3*), 214–9.*

Hansen. P.F.B., Andersen, K.H., Wieck-Hansen, K, et al. (1998). Co-firing straw and coal in a 150-MWe utility boiler: in situ measurements. *Fuel Process Technology,* 54 (1 – 3), 207–225.

Ionescu, G., Rada, E.C., Ragazzi, M., Marculescu, C., Badea, A., Apostol, T. (2013). Integrated municipal solid waste scenario model using advanced pretreatment and waste to energy processes. *Energy Convers. Manage.* 76 (December) 1083–1092.

Kemppainen, K., Siika-aho, M., Östman, A., Sipilä, E., Puranen, T., Von Weymarn, N., Kruus, K. (2014). Hydrolysis and composition of recovered fibers fractionated from solid recovered fuel. *Bioresource Technology*, 169 (10) 88–95.

Kloek, W., Jordan, K. (2005 ed.) Waste generated and treated in Europe – Data 1995–2003.

Lorber, K. E., Ragoßnig, A. (2012). Solid recovered fuels – "What's new?" *Waste Manage. Res.* 30 (4), 333–334.

Lund, H. (2007). Renewable energy strategies for sustainable development. *Energy*, 32 (6), 912–919. McDougall, F., White, P., Franke, M., Hindle, P. (2001). Integrated Solid Waste Management: A Life Cycle Inventory, second ed. Blackwell Science Ltd.

Menikpura, S.N.M., Sang-Arun, J., Bengtsson, M. (2013). Integrated solid waste management: an approach for enhancing climate co-benefits through resource recovery. *J. Clean. Prod.* 58 (11), 34– 42.

Montané, D., Abelló, S., Farriol, X., Berrueco, C. (2013). Volatilization characteristics of solid recovered fuels (SRFs). *Fuel Processing Technology* 113 (9), 90–96.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J. (2014a). Mass, energy and material balances of SRF production process. Part 1: SRF produced from commercial and industrial waste. *Waste Manage.* 34 (8)1398–1407.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J. (2014b). Mass, energy and material balances of SRF production process. Part 2: SRF produced form construction and demolition waste. *Waste Manage.* 34 (11) 2163–2170.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J. (2015a). Mass, energy and material balances of SRF production process. Part 3: SRF produced form municipal waste. *Waste Manage. Res 33 (2) 146–156.*

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M. (2015b). Elemental balance of SRF production process: solid recovered fuel produced form commercial and industrial waste. *Fuel* 145 (April) 1–11.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M. (2015c). Elemental balance of SRF production process: solid recovered fuel produced form construction and demolition waste. *Fuel* 145 (November) 280 – 288.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M. (2013). Quality of SRF produced from commercial and industrial waste and construction and demolition waste based on the mass, energy and elemental balance. In: 14th International Waste Management and Landfill Symposium, 30 September–4 October 2013, Santa Margherita di Pula, Cagliari, Italy Proceedings. CISA Publisher.

Pieber, S., Ragossnig, A., Pomberger, R., Curtis, A. (2012). Biogenic carbon-enriched and pollutant-depleted SRF from commercial and pretreated heterogeneous waste generated by NIR sensor-based sorting. *Waste Manage. Res*, 30 (4), 381– 391.

Quality Management, Organization, Validation of Standards, Developments and Inquiries for SRF (QUOVADIS). Report on the validation of the sampling procedures including recommendations to TC 343 for the eventual revision of the TS before its upgrade to a European standard (EN) WP 4 – sampling. Deliverable 4.3 2005; progressive number 20.

Rada, E.C., Ragazzi, M. (2014). Selective collection as a pretreatment for indirect solid recovered fuel generation. *Waste Manage*. 34 (2), 291–297.

Ragazzi, M., Rada, E.C. (2012). RDF/SRF evolution and MSW bio-drying. *WIT Trans. Ecol. Environ*. 163 (199), 208.

Rada, E.C., Andreottola, G. (2012). Editorial RDF/SRF: Which perspective for its future in the EU. *Waste Management,* 32 (6), 1059–1060.

Rechberger, H. (2001). An entropy based method to evaluate hazardous inorganic substance balances of waste treatment systems. *Waste Manage. Res.* 19 (2) 186–192.

Roos, H., Peters, W. (2007). Advanced processing production of municipal solid waste for the high-grade quality fuels. In: Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium, Margherita di Pula S, Cagliari, Italy, 1-5 October, 2007; CISA: S. Margherita di Pula S, Cagliari, Italy.

Rotter, V.S., Kost, T., Winkler, J., Bilitewski, B. (2004). Material flow analysis of RDF production processes. *Waste Manage*. 24 (10), 1005–1021.

Santibañez-Aguilar, J.E., Ponce-Ortega, J.M., Betzabe González-Campos, J., Serna-González, M., El-Halwagi, M.M. (2013). Optimal planning for the sustainable utilization of municipal solid waste. *Waste Manage*. 33 (12), 2607–2622.

The World Bank (2012). What a waste: a global review of solid waste management. Retrieved from <http://go.worldbank.org/BCQEP0TMO0>.
[accessed in 2015]

The Intergovernmental Panel on Climate Change (IPCC) (2006). IPCC Guidelines for National Greenhouse Gas Inventories. In: Eggleston HS, Buendia L, Miwa K, Ngara T, and Tanabe K (Eds.). The Institute for Global Environmental Strategies (IGES).

The European Parliament and the Council of the European Union (2007). European Parliament resolution on a Thematic Strategy on the recycling of waste (2006/2175(INI)). Official Journal of the European Union. 50:168–174.
United Nations (2013). *Greenhouse Gas Inventory Data - Comparisons by Category*. Available at from:
http://unfccc.int/di/DetailedByCategory/Event.do?event=go.
[accessed in 2015]

U.S. Department of Energy (2007). Methodology for allocating municipal solid waste to biogenic/non-biogenic energy. Washington, DC: Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels.

United States Environmental Protection Agency (2009). Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures for 2008. Washington: United States Environmental Protection Agency.

Vainikka, P., Enestam, S., Silvennoinen, J., Taipale, R., Yrjasa, P., Frantsi, A. (2011). Bromine as an ash forming element in a fluidised bed boiler combusting solid recovered fuel. *Fuel,* 90 (3), 1101–1112.

Vainikka, P., Hupa, M. (2012). Review on bromine in solid fuels – Part 2: anthropogenic occurrence. *Fuel*, 94 (April), 34–51.

Velis, C., Wagland, S., Longhurst, P., Pollard, S., Robson, B., Sinfield, K., Wise, S. (2011). Solid recovered fuel: influence of waste stream composition and processing on chlorine content and fuel quality. *Environ. Sci. Technol.* 46 (3), 1923–1931.

Velis, C., Copper, J. (2013). Are solid recovered fuels resource-efficient? *Waste Manage. Res.* 3 (2), 113–114.

Velis, C., Wagland, S., Longhurst, P., Robson, B., Sinfield, K., Wise, S., Pollard, S. (2013). Solid recovered fuel: materials flow analysis and fuel property. Development during the mechanical processing of biodried waste. *Environ. Sci. Technol.* 47 (6), 2957–2965.

Velis, C., Wagland, S., Longhurst, P., Robson, B., Sinfield, K., Wise, S., Pollard, S. (2012). Solid Recovered Fuel: Influence of Waste Stream Composition and Processing on Chlorine Content and Fuel Quality. *Environ. Sci. Technol.* 46 (3), 1923–1931.

Wua, H., Laurén, T., Yrjas, P., Vainikka, P., Hupa, M. (2014). Fate of bromine and chlorine in bubbling fluidized bed combustion – formation of alkali halide aerosols. *Fuel* 128 (July), 390–5.

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